MULTILAYER MATERIAL SYSTEM ANALYSIS OF WIND TURBINES

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PREFACE

This master thesis is the culmination of a two-year experience that has enabled me to dive deep into the challenging world of sustainability. I am grateful for the opportunity to learn how current companies and societies can become more circular and which are nowadays' challenges, especially at the European context.

I would like to acknowledge the task of the SINReM coordination and the EIT Raw Materials community, for providing the appropriate context and excellent resources to fulfil my goals in this program. I was lucky for being able to experience in real life how businesses are doing the transition to a more sustainable future with in-person site visits, as well as learning from some of the most prestigious European universities.

Secondly, I would like to thank my promoter and tutors from STEN group (UGent), Prof. dr. ir. Jo Dewulf, dr. ir. María Fernanda Godoy and ir. Célestin Demuytere, for all the knowledge they transferred to me and the guidance throughout all our meetings in order to develop this master thesis. This work is, to some extent, a direct result of their support and perseverance. At the same time, I truly appreciate the assistance received from dr. ir. Silvia Bobba of the Joint Research Center. It is worth mentioning that some of her colleagues from the JRC and Luca Ciacci, from the University of Bologna, have been really supportive in the acquisition of data. Part of these words of thanks go to them as well.

Finally, from a personal perspective, I would like to thank my family for all the support in this new chapter of my life, facing the challenge of distance with positivism and trust; as well as my master friends, for being like a second family and always ready for one more coffee, one more song and one more hug.

ABSTRACT

In order to accomplish the objectives of the European Green Deal, the European Union (EU) has a keen interest in enhancing the deployment of wind turbines (WT), which brings a considerable material challenge. This master thesis aims at analysing the flows and stocks of the life cycle of WT in the EU, for the technology as a whole and for specific critical raw materials. To do so, a multilayer Material System Analysis in the EU28 in 2016 was conducted. For this methodology, the following layers were defined: the “grandparent” layer corresponds to the entire material cycle for wind turbines, the “parent” one differentiates between gearbox and direct drive types and the raw materials layers get specified with nickel, manganese and neodymium.

The main outcomes of this work are that 2117 kt of material are needed in the manufacturing phase, from which 7800 t, 15200 t and 700 t correspond to Ni, Mn and Nd respectively. The EU is a consolidated manufacturer of the main components and assemblies of WT, yet faces some geopolitical challenges. For instance, the supply chain of permanent magnets is controlled by China, and the EU lacks a consolidated magnet industry, therefore their procurement might be an obstacle. Other crucial aspects examined in this study were the failure rate of WT components, the end-of-life pathways of various materials and the comparison of the selected materials' roles in other applications, among other key considerations.

TABLE OF CONTENTS

TABLE OF FIGURES AND TABLES

FIGURES

TABLES

LIST OF ABBREVIATIONS

Abbreviation	Meaning
CRM	Critical Raw Materials
DD	Direct Drive
DfE	Design for the environment
DFIG	Double-Fed Induction Generator
EESG	Electrically Excited Synchronous Generator
EC	European Commission
EoL	End-of-life
EoL-RR	End-of-life recycling rate
EU	European Union
GB	Gearbox
GWEC	Global Wind Energy Council
HAWT	Horizontal-axis wind turbine
HS	Harmonized Commodity Description and Coding System
HSS	High-strength steel
IE	Industrial Ecology
IO	Input-output
JRC	Joint Research Centre
LCA	Life cycle assessment
LIB	Li-ion batteries
MFA	Material Flow Analysis
MSA	Material System Analysis
NG	Natural graphite
PM	Permanent Magnet
PMSG	Permanent Magnet Synchronous Generator
PV	Photovoltaics
RED	Renewable Energy Directive
REE	Rare-earth elements
SCIG	Squirrel Cage Induction Generator
UK	United Kingdom
US	United States
VAWT	Vertical-axis wind turbine
WRIG	Wound Rotor Induction Generator
WT	Wind turbine

LIST OF PARAMETERS USED IN THE MATERIAL SYSTEM ANALYSIS METHODOLOGY

Table 1 List of parameters (flows and stocks) included in the Material System Analysis (MSA) methodology (explanation in section 4.1). The strikethrough text indicates items that are out of the boundaries of this study.

C. Processing	M.2.1 Processed material sent to manufacturing
D. Manufacture of end-products	D.1.1 Production of manufactured products in EU send to use in EU
	D.1.2 Exports from EU of manufactured products
	~~D.1.3 Imports to EU of processed material sent to manufacturing~~
	D.1.4 Manufacture waste in EU sent for disposal in EU
	D.1.5 Manufacture waste in EU sent for reprocessing in EU
	D.1.6 Exports from EU of manufacture waste
	D.1.7 Output from the value chain at manufacturing step
	~~D.1.8 Imports to EU of products requiring further manufacturing steps in the EU~~
	~~D.1.9 Imports of secondary raw material sent to manufacturing in the EU~~
	M.3.1 Manufactured products sent to use in EU
E. Use	E.1.1 Stock of manufactured products in use in EU
	E.1.2 Stock of manufactured products at end-of-life that are kept by users in EU
	E.1.3 Exports from EU of manufactured products for reuse
	E.1.4 Imports to EU of manufactured products
	E.1.5 In use dissipation in EU
	E.1.6 Products at end-of-life collected for treatment in EU
	E.1.7 Annual addition to in-use stock of manufactured products in EU
	E.1.8 Annual addition to end-of-life stock of manufactured products at end-of-life that are kept by users in EU
	M.4.1 Products at end-of-life in EU collected for treatment
F. Collection (end of life)	F.1.1 Exports from EU of manufactured products at end-of-life
	F.1.2 Imports to EU of manufactured products at end of life
	F.1.3 Manufactured products at end-of-life in EU sent for disposal in EU
	F.1.4 Manufactured products at end-of-life in EU sent for recycling in EU
	F.1.5 Stock in landfill in EU
	F.1.6 Annual addition to stock in landfill in EU
G. Recycling	G.1.1 Production of secondary material from post-consumer functional recycling (old scrap) in EU sent to processing in EU
	G.1.2 Production of secondary material from post-consumer functional recycling (old scrap) in EU sent to manufacture in EU
	G.1.3 Exports from EU of secondary material from post-consumer recycling
	G.1.4 Production of secondary material from post-consumer non-functional recycling in EU
	G.1.5 Recycling waste in EU sent for disposal in EU

1. INTRODUCTION

In 2019 the European Union (EU) committed to developing a society with economic growth and achieving net zero greenhouse gases emissions, as outlined in the European Green Deal [1]. One of the pursued strategies is to consolidate a strong renewable energy sector, led by solar and wind power. In particular, the initiative REPowerEU Plan is specifically designed to achieve three clear goals: to save energy, to produce green energy as a viable alternative to fossil fuels and to diversify energy supplies [2]. These demonstrates that energy is at the top priority list of EU's political agenda.

Wind energy has a rich story that originated in Europe, marking an innovation success journey that continues to hold immense potential for further advancements [3]. Currently, it has a direct impact in EU's economy: it creates more than 300 thousand jobs, contributes with 37 billion € to EU's gross domestic product and generates 5 billion € in local taxes every year [4]. Furthermore, European wind energy is an international reference: for instance in 2017 EU's top wind turbine manufacturers accounted for 56% of the global market share [5]. Wind can allow the EU to have a source of energy clean, secure and that maintains them independent in terms of power supply [4]. Therefore, it is crucial that the European Commission (EC) keeps on prioritizing wind energy in the policy-makers' agendas and providing the sector with the necessary resources, societal transformation and regulatory framework [6].

Nevertheless, despite the targets set by the EC initiatives, wind turbines still have many obstacles to overcome from both technical and logistical points of view. Particularly, the sector has specific requirements for raw materials and components used in wind turbines which might create a dependency with non-EU countries. In addition, it is facing challenges arising from inflation, supply chain disruptions, and increasing competition from more affordable Chinese manufacturers [7]. To unveil these barriers, the analysis of wind turbines' material flows along the life cycle arises as an indispensable method. Some key questions that emerge include how much material is managed in each phase, which technology type and therefore material demands are annually necessary, whether there is trade of material at any point of the supply chain or not, and whether functional recycling takes place, among others. The analysis should encompass not only the overall material composition of wind turbines but also focus on particular raw materials, considering their criticality as part of wind turbine components. This is the case for example of the rare earth elements (REE) present in the permanent magnets of certain generators, where the supply chain is mainly dominated by China [8].

This project aims at analysing the EU's supply chain flows and stocks of materials in the wind turbine industry. By doing so, valuable insights can be gained, shedding light on the current state of the wind energy sector in the EU and giving support to resource-management policies to further advance the sustainable growth of wind energy.

2. LITERATURE REVIEW

2.1. Wind turbine technology

2.1.1. Parts and definitions

A wind turbine (WT) is a technology capable of transforming wind and kinetic energies to mechanical power, ultimately generating electricity. Overall, the design of WT must aim to achieve optimum operation, that is, to maximize the conversion of wind to electrical energy, while avoiding faults. Their potential for providing society with green energy must be evaluated with a three-fold approach: efficiency of wind power use, reliability and safety [9].

The technology consists of four main parts: foundation, tower, rotor, and nacelle, these last two containing the various electrical and electronic elements.

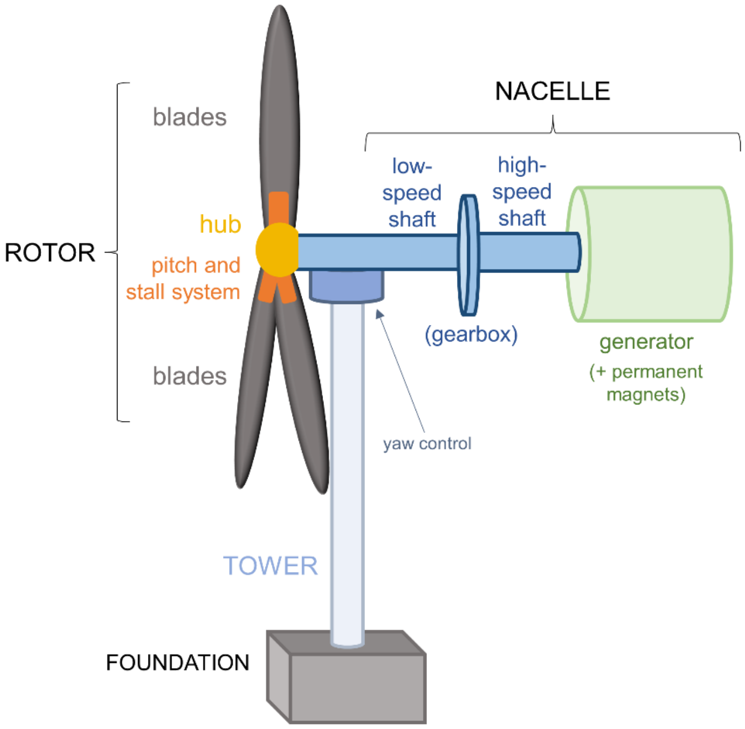

Figure 1 Diagram with the main components of a WT. Note: gearbox and permanent magnets are just present in some WT types.

A diagram of the main components of a WT can be observed in Figure *1*. As can be noted, the rotor, which comprises the blades, hub and the blade pitch and stall system, is attached to the nacelle. The hub is the contact part between the rotor blades and the nacelle; and the tower connects the nacelle with the foundation. Other additional elements (not depicted in the figure) include an anemometer and wind vane, to measure the speed and direction of the wind, respectively, the brake, aviation lights and a battery backup, among others.

As part of the rotor, the blades are long structures which receive the wind force and use it to spin. They are mainly composed by reinforced fibres (glass, carbon, aramid or basalt) and a polymer matrix (thermosets such as epoxies, polyesters, vinyl esters, polyurethane or thermoplastics). Blades also contain a sandwich core (balsa wood or foams like polyvinyl chloride and polyethylene terephthalate), some coatings (polyethylene and polyurethane), and metals such as copper wiring and steel bolts [10].

Depending on the relative position of the blades with respect to the wind direction (i.e. the axis of rotation), there are horizontal-axis turbines (HAWT), in which the axis of rotation is almost parallel to the flowing direction of air stream; and vertical-axis turbines (VAWT), in which the axis of rotation is vertical to the ground and almost perpendicular to the wind direction. The design and installation of HAWT is more complex and requires larger space than the one for VAWT. In addition, VAWT produces less noise, its maintenance is easier, it does not require pitch control nor yaw drives, is less hazardous for birds and is cheaper. Nevertheless, HAWT have much higher power coefficient, thus enabling it to be the most appropriate option for wind energy solutions [11]. Therefore, all the following analysis is focused on HAWT.

In order to generate economically feasible energy, WTs are manufactured to operate at maximum output with wind speeds around 15 m/s. This is a reference value, heavily contingent on the specific location of the installation [12]. Therefore, WT need power control technologies to curtail part of wind's excess energy when the wind is too strong (to avoid damaging the WT) and to regulate the blades spinning if the wind is weaker than expected. The usual power control systems are pitch, stall and yaw control [11]; all represented in Figure *1*. The pitch consists in modulating the angle of rotor blades with respect to the wind so that the rotor speed and the generated electrical energy remain in the desired levels. The stall control is able to tilt the blades in the opposite direction from what the pitch control does, forcing them to go into a "deep tall" situation. It is especially useful when the equipment achieves its maximum power [13]. Last but not least, the yaw control aims at aligning the rotor axis with the wind direction and it can also be used for power regulation [14].

The tower is the component functioning as the structure, holding the blades and nacelle at around a hundred meters above the ground / water. Usually WT also contain foundations, that fix the base to the ground or seafloor [15].

Finally, the nacelle is the enclosed chamber where the power generation takes place. It contains low- and high-speed shafts and sometimes a gearbox, which altogether transmit and boost the kinetic energy accumulated by the blades (see Annex for further explanation). The direct drive turbines do not contain a gearbox. The drive train system or generator is in charge of converting the mechanical energy to electrical one, which is then transported to the power station by copper cables [16]. Its composition strongly depends on the type of drive train system that the WT contains. Each wind turbine is characterized by a nominal power, which is the power at which it operates in standard conditions, the ideal one for high electricity generation without incurring damage.

2.1.2. Onshore versus offshore wind turbines

Focusing on the location of the equipment (i.e. application), wind turbines are onshore (on land) or offshore (in the sea or ocean), being this distinction the most well-known way of segregating the market. The offshore type can be fixed with foundations or floating. There are 5 main types of fixed-bottom foundation technologies (gravity-base, monopile suction bucket & tripod, high-rise pile cap and Jacket) and three floating ones (semi-submergible, spar and tension-leg platform) [17]. Floating designs mainly consist of an individual buoyant platform, whose stability is achieved by maintaining most of the structure underwater, connected to the seabed by anchoring cables [18]. This type is necessary for wind energy generation in deep water areas, which correspond to more than 60-80 m in depth. A graphical representation of onshore, offshore fixed and offshore floating WT is shown in Figure 2 [19].

Figure 2 Representation of onshore, offshore fixed and offshore floating WT [19].

Nonetheless, floating offshore wind in 2022 in Europe just represented 113 MW [20], so it is still developing and does not represent a relevant share of wind energy. Therefore, floating turbines are not assessed in the following review (nor in the analysis).

Onshore and offshore wind turbines have benefits and drawbacks, that should be placed within the appropriate context. They are summarized in Table 2.

Starting with the onshore sites, their main advantage is low cost: production and installation are much cheaper than in the offshore case. In addition, onshore maintenance is easier because the facilities can be directly accessed in some minutes or a few hours directly by road communication, whereas offshore tasks require specialized human resources, expensive equipment and complex transportation (boat commute while coping with maritime weather). Their main disadvantages are the low strength and reliability of wind as well as the challenging planning permissions mainly due to environmental and social concerns [21] [22].

Offshore sites, in turn, present much more beneficial wind features: faster, more reliable and more stable [23]. According to the Global Wind Energy Council (GWEC), offshore wind energy sites have enough energy potential to provide 7 times the current global energy demand, and mean wind speeds are much higher than those in onshore sites [24]. This is also influenced by the characteristics of an offshore area: with no buildings, nor mountains or hills to interrupt it, wind flows purely following the natural trends, which makes them much easier to predict than in onshore sites. From a logistics point of view, some of the world's largest cities are coastal; therefore, offshore generation could be located relatively close to high spots of electricity consumption [18] (even though not all seaside areas are appropriate for wind energy). Finally, offshore projects are accepted with more likelihood by the public sector [21][25] and it is reported that they require less exclusion and assessment criteria compared to onshore [26].

The main disadvantage of installing offshore is the high production and installation cost, which has caused a slow development of offshore projects in non-EU countries. In addition, as a considerable amount of resources are mobilized and a strong coordination is needed specially in offshore, there is a high risk that supply chain disruptions may complicate or even postpone their fabrication and installation [27]. In addition, the criticality of its manufacturing materials in terms of economic importance and supply risks will be a remaining adverse circumstance [28].

Table 2 Comparison between onshore and offshore according to several aspects (first column). Advantages are indicated in green and disadvantages in orange. Sources of information are specified in the text above.

	Onshore	**Offshore**
Location	**Land**	**Sea / ocean**
Wind characteristics	Less strong	More reliable, fast and stable
Public acceptance	Lower	Higher
Amount of site selection criteria	Higher	Lower
Material criticality	Lower	Can be challenging
Installation costs	Lower	Higher
Maintenance	Easier	Logistically challenging and expensive

Wind turbines are usually installed in a wind park. The selection of its appropriate location is a key decision in a wind energy project. The main parameters that should be taken into account are the WT nominal power, physical dimensions and purchase cost, the available area and geographical peculiarities of the wind park's installation site, the wind potential, the social and environmental drawbacks of that area, the site accessibility and the delivery time of the manufacturer [11].

2.1.3. Drive train systems

Diving into the technology specifications, an essential part of wind turbines is the drive train system, composed of the gearbox (if any), the electric generator and the power converter (if any) [29] [30]. The technology is commonly divided in gearbox and direct drive train (gearless) systems [31] and a diagram of both types of configuration is presented in Figure 3 [32].

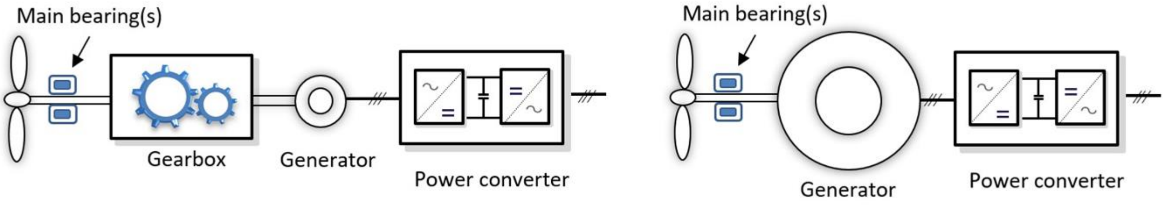

Figure 3 Diagram of the two main types of drive train systems: gearbox (left) and direct drive (right). Ref.: [32]

The function of the generator is to convert mechanical into electrical energy. Its operation is based on the "electromagnetic induction" principle: if an electric conductor and a magnetic field undergo relative movement, an electric current is induced in the conductor [11].

The depiction of the different drive train types and their connection with the generator technologies is presented hereunder, with a schematic summary in Figure 4 [31].

- **Gearbox (GB)**, which is usually classified as medium-speed (> 80 rpm) or high-speed (> 900 rpm). As its name indicates, gearboxes are used to increase the frequency of the rotor shaft, transferring power from the low-speed turbine shaft to the high-speed generator shaft [33]. They can have electrically excited synchronous generators (EESG), contain permanent magnets (medium or high-speed and abbreviated PMSG), or electromagnet generators (high-speed). This last type is based on induction, which can consist of a Double-Fed Induction Generator (DFIG), used in variable speed machines, a Squirrel Cage Induction Generator (SCIG), used in constant speed WT, or a Wound Rotor Induction Generator (WRIG), which includes the external mechanism to control electrical characteristics. WRIG are more costly than SCIG and their structure is not as robust and simple [34]. GB configuration is heavy and requires substantial maintenance, so it is less competitive in larger farms and offshore locations [35].
- **Direct Drive (DD)**, which contains permanent magnet synchronous generators (PMSG) or can incorporate an electrically excited synchronous generator (EESG). They are gearless, so instead of using a gearbox, the rotor is directly connected to the generator (right side of Figure 3), implying that the generator speed is equivalent to the rotor speed [36]. The frequency of the generated electricity is increased until the desired value by using a large number of magnetic poles (more than 60), reason why it is also called multi-pole low speed generator. Even though it implies a larger size and weight of the equipment, the gearless design demands less intensity in the maintenance requirements, becoming a desired option for offshore applications [37].

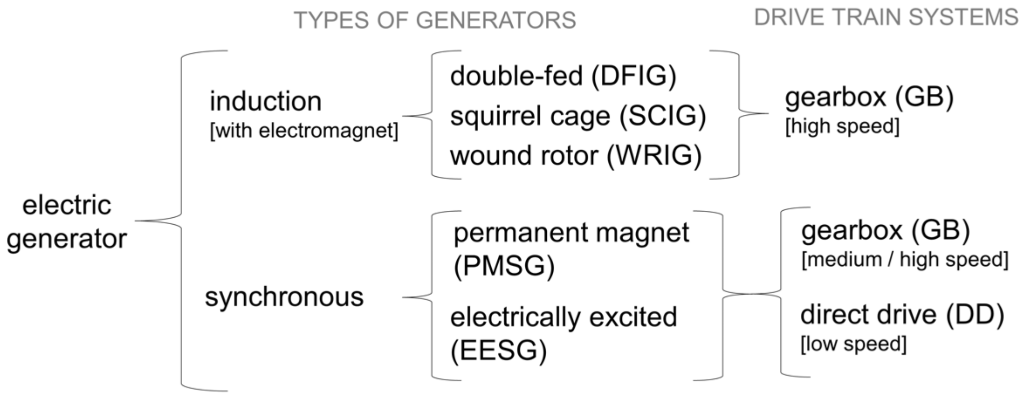

Figure 4 Classification of the types of generators and drive train systems. Own figure, based on: [31]

Recently, there is a trend towards DD generators due to several factors. First, because of its complex structure, the gearbox type needs much more maintenance. In fact, they are considered the most failure-prone components and are usually replaced once during the WT lifetime [33]. Second, gears are expensive and substantially increment the total cost of the system. Third, the operating speed range and the grid integration might be limited [38]. Nevertheless, DD mainly use permanent magnets, which contain some critical raw materials. Therefore, their major challenge is the price and availability of components. This will be further explained in section 2.1.4 [11].

For onshore applications, the GB type is more preferred than the DD (77% against 23% of market share each of cumulative WT in 2016); with most of it corresponding to GB-DFIG and almost equal share of GB-PMSG and GB-SCIG [16][29]. Concerning the DD usage, most of it is EESG [16]. For offshore, DD technology turns out as the most appropriate due to its lower trend to failure, robustness and less energy losses during transmission when compared to GB. In addition, gears are expensive and significantly increase the overall cost. Therefore, due to its high efficiency and reliability, the current technology trend is towards DD turbines with PMSG, but in the cumulative installations the GB technology is still predominant [39]. According to the Joint Research Centre (JRC) of the European Commission (EC), around 50% of offshore WT newly installed in 2016 were GB-SCIG, but in 2018, 70% were DD-PMSG [16]. The possible future evolution of this trend is presented in section 2.3.3.

2.1.4. Materials

WT are composed of 25000 components [16][40], usually grouped in the abovementioned parts: rotor, tower, nacelle and foundation. If present, the greatest share of materials corresponds to the foundation, around 75% of the overall mass [21][22]. Putting aside the foundation, from the rest of the mass the rotor and nacelle conform 20% each, and the tower the remaining 60%. Regarding the involved types of material, Figure 5a shows the material intensity in t/MW, i.e., the tons (mass) of each raw material per unit of installed capacity [16].

Wind turbine’s material content has largely varied over time as new technologies arose. The presented data corresponds to the average composition of the main types of generators: DD-EESG, DD-PMSG, GB-PMSG and GB-DFIG [16]. The presented graph gives some insights on the importance of each material: concrete and steel cover most of the composition, representing 91.4% of the total mass. Following, cast iron (Fe), glass and carbon composites as well as zinc (Zn) have significant relevance. The rest represent around 2% of the mass.

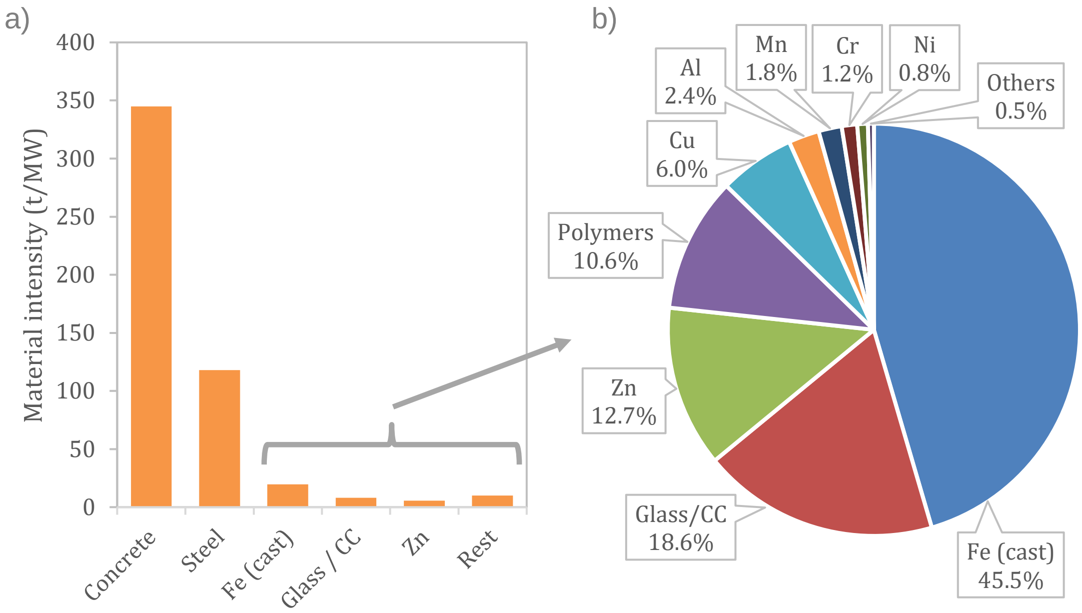

Figure 5 a) Material intensity in t/MW of installed capacity. b) Without considering concrete and steel, shares of the rest of materials present in WT. Note that CC corresponds to carbon composite. Ref.: [16].

For a more detailed view, Figure 5b presents the shares of the materials present in WT, without considering concrete nor steel. The presence of metals is led by cast Fe and Zn, followed by copper (Cu), aluminium (Al), manganese (Mn), chromium (Cr) and nickel (Ni) [16]. In order to determine the importance of each material in a WT, it is necessary to take into account not only its amount in the turbine but also in which component(s) it is present and its role in the technology. Following, a more detailed explanation of the function of some elements is given:

- **Concrete**: its presence is due to the foundations. In onshore applications, foundations are gravity-based (100% concrete) or rock-anchored steel (with 5% steel) and concrete platforms [16].
- **Steel**: in offshore applications, the mostly used type of foundation is monopile, made up of massive low-alloyed steel cylinder anchored directly to the seabed [16]. The remaining types of foundations (suction bucket and tripod, high-rise pile cap and jacket) are composed of a mix of steel (40-85%) and concrete [42]. The tower in both onshore and offshore is fabricated with large tubular steel sections as well. The nacelle has around 20-40% of steel (depending on the generator type) and the blades around 20% [21][23]. On average, more than 80% of the wind turbine is made of steel and cast iron.

- **Iron**: in the case of Fe, the relevance lies in its use for the nacelle structure, between 35% and 50% of its mass. In the case of PMSG generators, Fe is also a crucial part of permanent magnets (PM), covering 66% of their composition [43].
- **Carbon composites (CC) and glass**: they compose the fourth group of materials with greatest importance. Composites are mainly used in the blades, nacelle and hub covers. In particular, the hub cover is composed of glass-fibre-reinforced polyester and the nacelle cover with woven glass fibres, polyethylene and styrene [41].
- **Polymers** (thermoset and thermoplastic resins): they cover around 1% of the of the total mass, with a particular importance in the rotor (blades fibre) and along with aluminium (Al), copper (Cu) and steel are used for the production of cables for the electric plant [44]. No considerable differences in glass, CC nor polymers composition are estimated among different technologies.
- **Zinc**: Zn has a crucial function because it is used as a corrosion protective coating. WT are exposed to severe climatic contexts and mechanical stresses; therefore, to ensure their preservation is necessary to provide the structure an extra coat, usually made of Zn. In addition, it can lengthen the turbine's lifetime [45].
- **Aluminium and copper**: Al is crucial to fabricate lightweight as well as resistant components, like the ones required in the tower, blades and nacelle, and it is also used for cabling. Cu is necessary in the coil windings of the stator and rotor parts of the generator, in the cables for the high-voltage power, transformer coils and grounding system. The presence of both Al and Cu vary a lot depending on the type of WT. In the case of DD turbines, Al is present in a lower composition and Cu in a higher one [35]. The opposite takes place for the GB type, where there is a certain substitution of Cu with Al in the transformer of the nacelle and in the tower design. In some cases, the use of Al can even exceed 3500 t/GW, a trend that some manufacturing companies are promoting [16].
- **Manganese, nickel and chromium**: they are mainly present alongside some steel elements; therefore, a higher content is present related to components with high-alloy steel. A further analysis of Mn and Ni role in WT is presented in section 2.2.
- **Boron** (B) and **rare-earth elements** (REE): these elements are fundamental in permanent magnets, even though present in a low percentage compared to other materials. REE are 30% of the overall composition of PM, being B just 1% and Fe the rest. Specifically, neodymium (Nd) represents almost 70% of all the REE utilized, followed by praseodymium (Pr), dysprosium (Dy), gallium (Ga) and terbium (Tb). In the case of Nd, its composition is more than double in DD generators compared to GB. Overall, PM weight around 4 tons [46]. In addition, some REE are also used for the magnets inside the turbine tower, for attaching internal fixtures [41].

2.2. The role of specific materials: nickel, manganese and neodymium

As presented in the previous subsection, Ni, Mn and Nd are part of the main composition of WT, primarily found in the rotor and nacelle. In particular, Ni is present in a range of 340 - 440 t/GW, Mn in quantities around 790 t/GW and Nd in a much lower concentration, of around 12-180 t/GW, depending on the type of drive train system [16].

In addition to their presence in WT, Ni and Mn are also present in automotive [47], energy [48] and digital industries [49], as well as construction and energy intensive industries. They are important elements in the global and European market. Globally, in 2021 Mn was the 5th most mined metal in the world, accounting for 11% of the total tons, while Ni was in the 9th position, corresponding to 1.5% of the global total metal extraction [50]. In the case of Nd, its market relevance is mostly related with its presence in permanent magnets. It is a key enabler of the energy transition due to its application in electric motors and wind turbines [51]. In order to achieve the climate ambitions, Nd's demand could increase tenfold by 2030 [28].

From the European Union's (EU's) perspective, a special focus should be given to critical raw materials (CRM) because they are necessary for the strength of EU's economy. A reliable and solid supply chain of CRM should be guaranteed. They are those that present a high economic importance in EU's industrial sectors, together with a high supply risk. The fifth and most recent CRM list was published in 2023 and it consists of 34 raw materials that were classified in the criticality zone [52], which means a "Supply Risk" (SR) factor greater than 1 and an "Economic Importance" (EI) factor greater than 2.8 [53], [54]. The three elements Mn, Ni and Nd are assessed as part of the CRM list in the abovementioned last edition.

In the case of Mn, its EI indicator was already higher than the criticality threshold limit in the previous list and became finally completely critical due to the SR factor increase. In particular, this raise took place because of tension on the extraction stage, caused by lower domestic supply dropping from 32 t to 10 t, increasing import reliance and by more concentrated imports from South Africa and Gabon [54]. In the case of nickel, it is the only battery material that had never been in the list before due to a diversified supply. However, it has been assessed as potentially critical due to the high concentration of ownership of production and refining projects (33% of the refiners are in China) and due to private contractual arrangements. It is included in the list as strategic raw material, in line with the Critical Raw Materials Act [52]. Therefore, the criticality assessment has been complemented with a forward-looking analysis of selected strategic technologies and sectors [8], which classifies several raw materials as strategic, among which Ni and Mn are included.

In the case of neodymium, it was already part of the CRM list in previous editions and its criticality increased from 2020 to 2023. In particular, the EI increased from 4.8 to 7.2 due to the evolution of end uses shares towards magnets sector, as stated in the “Study on the CRMs for the EU” [52]. 85% of the EU supply of Nd comes from China, so it is highly dependent on imports [52].

Following, the depiction of each raw material supply chain and market is presented. The information is shown graphically for the cases of Ni and Mn in Figure 6 [55], with EU as system boundaries.

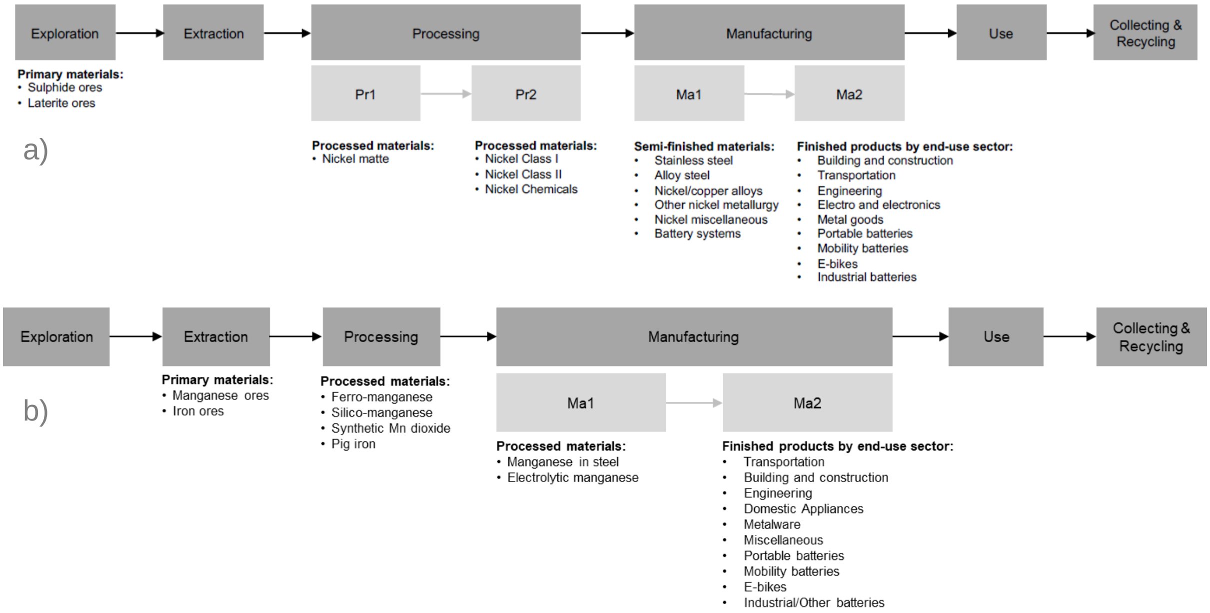

Figure 6 Value chain in the EU for a) nickel, b) manganese. Ref.: [55]

The nickel value chain (Figure 6a) starts with the exploration and extraction of its primary materials: sulphide (73%) and lateritic ores [56]. It is mined in more than 25 countries worldwide and the world’s Ni production is over two million tons. 80% of all the Ni historically mined has been extracted in the last three decades, and its demand is increasing mainly due to the growing demand of stainless steel for the automotive industry. Its processing consists of smelting and refining stages, which produces firstly Ni matte and secondly Ni Class I (i.e. pellets, granules, powder, etc.), Ni Class II (i.e. ferro-nickel and Ni oxide sinter), and nickel chemicals (such as sulphate, chloride, carbonate, etc.). The manufacturing phase covers the fabrication of semi-finished and finished products. According to the Nickel Institute [57], semi-finished products are allocated to stainless steelmaking (69%), battery systems (11%), Ni/Cu alloys (7%), plating (6%), alloy steels (7%), foundry (2%) and others. In stainless steel production, not all Ni input comes from primary Ni and a ratio of 2:1 new scrap to old scrap is estimated [57].

Following, some end-use sectors in which Ni is present are transportation (mainly electric vehicles), building and construction, engineering, domestic appliances, metalware, etc. The in-use stock of Ni in the EU in year 2016 was estimated at 7100 kilo tons of Ni equivalent [55]. Finally, the end-of-life collection and sorting percentages depend on each industrial sector.

The one with the highest efficiency rate is mobility batteries (95%), while the ones with the lowest are portable batteries (45%) and e-bikes (50%) [58] [59].

The country with highest market share in manufacturing is China, due to the growing technological level of stainless-steel production, the advancement of the automotive and construction industries, more infrastructure and the improvement of R&D activities. In America, U.S. is the leading country, as well with a huge boost of stainless steelmaking. On a business level, some of the key players are Anglo American plc, BHP, Vale and Eramet [60].

In the specific case of wind turbines, the presence of Ni is linked to mainly two types of material: Austempered Ductile Iron (ADI) and carburizing steel. ADI is a cast iron with a matrix of ferrite and austenite that contains carbon as graphite nodules. It is present in the gearbox, nacelle cover, rotor hub and main shaft [61]. A standard gear steel is also carburizing steel 18CrNiMo7-6, which is heat-treatable and is also present in screws [61].

The manganese value chain (Figure 6b) begins with its extraction of Mn as well as Fe ores. Major producers of Mn ore include South Africa, Australia, Brazil, Gabon and Ghana [62]. The primary form (for example oxide) is processed to deliver intermediate forms such as ferromanganese and silicomanganese alloys, which account for more than 75% of the total [63]. The processing outputs are mainly used for the steel industry as an alloying element as well as deoxidizing and desulfurizing agent. Apart from steel products, its main industry, Mn is also present as a semi-finished product in battery systems. Considering the type of Mn input, around 70% is new scrap, while the remaining corresponds to secondary Mn (old scrap) [64]. Following, the main end-uses of Mn are construction, transportation, engineering, domestic appliances, metalware, portable batteries, mobility batteries, e-bikes and industrial batteries. The in-use stock of this metal in EU in 2016 was $35 \cdot 10^6$ tons of Mn equivalent. Finally, the average rates of end-of-life collection and sorting are similar to the Ni case [55]. From a market point of view, the growth of the production of steel, and therefore of manganese, is potentiated by the construction and automotive industries. In addition, Mn alloys are increasingly being used for chemicals, dyes, fertilizers, animal feed, and dry cell batteries. The manufacturing of these products is mainly concentrated in China (70% of the silicomanganese type) and India (12%). In the case of ferromanganese, half of the global production is located in these two countries [63].

In WT, manganese is present in the tower, gearbox and in several nacelle parts and it is contained mainly in two material types: quarto plate (with standard steel grades S235, S275 and S355 [65]), and seamless rolled ring steels (e.g. 34CrNiMo6 or 18CrNiMo7-6 [66]).

In the case of neodymium, its value chain starts with the concentration steps of monazite and bastnaesite, which contain rare earth minerals. They are chemically digested with acids (to soluble sulfates or chlorides) or alkalis (to hydroxides). Leaching is carried out afterwards to remove impurities. For the extraction of individual REE, selective separation takes place with solvent extraction and solid-liquid systems. For the obtaining of high-purity metal, neodymium oxide (Nd_2O_3) is dissolved into molten fluoride prior electrolysis to metallic Nd [67]. Due to the large magnetic moment of Nd, it becomes the perfect candidate for magnet applications [68]. NdFeB, the most commonly used permanent magnets, follow a powder metallurgical route to become sintered or resin-bonded magnets. Afterwards, the product is magnetized by a magnetometer [69]. Nd is also employed in other applications, such as glass manufacturing, lasers production, high performance alloys resistant to corrosion in high temperature environments, ceramic and precious metal capacitors. It is also used in fluid catalytic cracking to refine crude oil and obtain more valuable commodities and in zeolites treatment [70].

2.3. Wind turbine market

2.3.1. Global overview

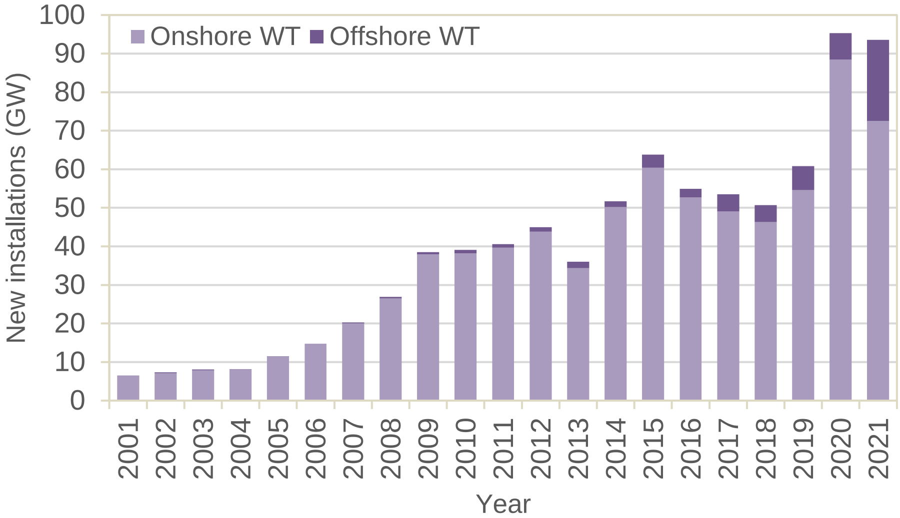

Figure 7 Global evolution of new WT installations since 2001. Onshore (blue) and offshore (red) types can be differentiated. Ref.: [24]

The rapid global evolution of green energy is an undeniable fact which has been potentiated by the development of wind turbines. In the last 30 years, WT nominal power has evolved from 50 kW to 15 MW, as well as a rotor diameter increase from 15 m to 236 m [11] [71].

In 2021 the total global wind energy capacity hit 837 GW [24]. The year with highest number of new installations was 2020, with a 57% increase with respect to the previous year. Differentiating the two types of WT locations, the global evolution of the last 20 years can be observed in Figure *7*. Onshore technology had its second-best year, with 72.5 GW in new installations in 2021. Moreover, the number of offshore new installations was the highest ever, corresponding to more than 21 GW and tripling the numbers of the previous year.

As illustrated in Figure *7*, the onshore market had a decline in 2021, mainly due to the deceleration of the two largest wind power markets, China and the United States (US). In the case of China, the National Development and Reform Commission and the National Energy Administration set 2020 as the limit for renewable Feed-in Tariffs, in order to shift green energy cost to grid parity or market-based prices [1] [72].

By contrast, in the US the wind market was expected to be strong and growing, led by the renewable electricity Production Tax Credit, which provides economic advantages to produced green energy [73]. However, the US experienced a drop in WT new installations due to supply chain issues and other complications caused by the COVID-19 pandemic, which pushed some projects to delayal and postponing. In particular, 5 GW of onshore wind projects with initial commercial operation date in 2021 were held up until the following year.

Focusing on the offshore market, a historical record increase was achieved, reaching a total offshore wind capacity of around 57 GW. Eighty percent of the newly installed infrastructure corresponds to China, who leads the market for the fourth year in a row. This boost originates from the same type of policies that promoted the onshore market in 2020: the renewable Feed-in Tariffs [72].

Concerning the total WT installations running in 2021, as shown in Figure 8a, the global onshore wind market is led by China and the US, owning 40% and 17%, respectively. Germany and India hold more than 5% of the total installations each. The rest of the picture is really diversified, with countries mainly from Europe, but also Americas and Asia.

In the case of offshore (Figure 8b), the United Kingdom (UK) plays a much more important role, holding a 22% of the total share, in second place after China, which continues leading with nearly 50% of the installations [24]. A considerable share of the total offshore energy is installed in Europe, which will be commented in detail in the following section 2.3.2. The offshore scene is completed by minor installations in Vietnam and Taiwan, with some delays and disruptions mainly due to COVID-19 effects. It is worth mentioning that the floating wind market is gaining track: the ongoing TetraSpar Norwegian project (3.6 MW) [74], five systems (under development) in Kincardine (Scotland) with five turbines of 9.5 MW each [75], and a pilot unit in a Chinese wind farm [76], bring up a total of 57 MW of global floating capacity commissioned in 2021.

Overall, the top five markets alongside with China are the US, the UK, Germany and India; in order of importance. The Asia-Pacific region is the world leader, while Europe hosts a 28% of the total installations. It should be noted as well that Latin America and Africa & Middle East

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[1] Grid parity takes place when the price of alternative energies (such as wind or solar) is less than, or equal to, the one from conventional sources. Market-based means prices set by similar products available in the market.

also had a record year of new installations in 2021, but still being at the lowest positions when compared to other regions.

With regard to the main global players, some of the leading companies in the sector (with their respective installed capacity in brackets) are: Vestas (160 GW), with nearly 30 thousand employees manufacturing the largest WT [77]; Siemens Gamesa (120 GW), engineering, building and delivering wind solutions [78], and General Electric Renewable Energy (62 GW), which are specialised in many green energy technologies [79].

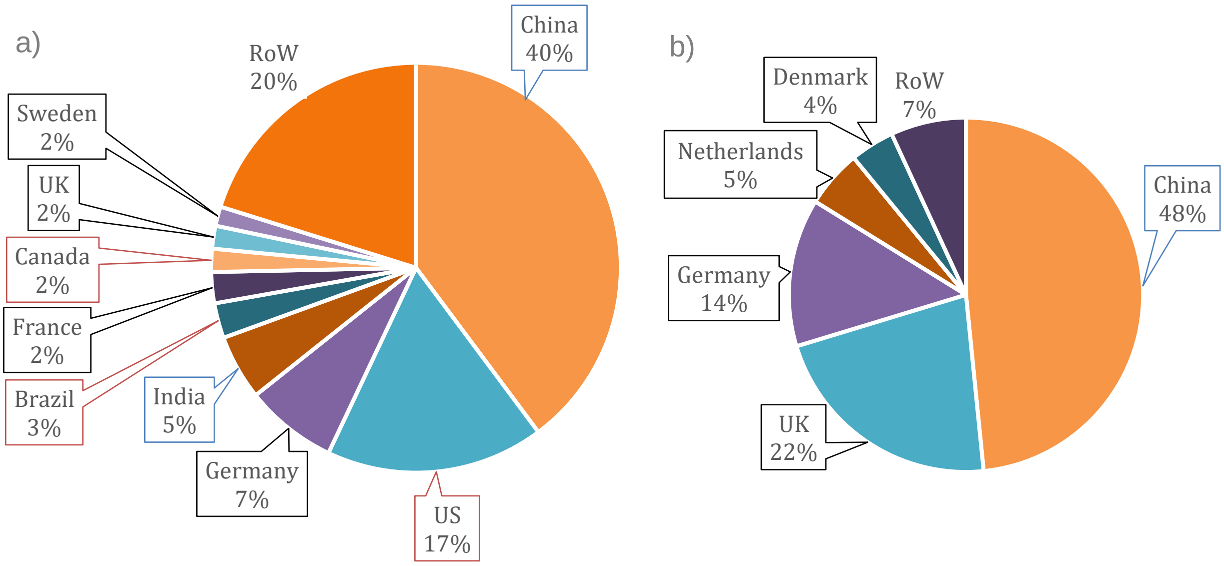

Figure 8 Shares per country of a) onshore and b) offshore, total wind capacity in 2021. Continents are represented with label colours: Asia (blue), Americas (red) and EU (black). RoW: Rest of the World. Ref.: [24]

2.3.2. European Union market

As already introduced in the previous section, Europe is the second global leading continent in wind energy. This position comes from a long history of policies and directives that promoted this technology among European countries. In 2009 the European Union (EU) approved the Renewable Energy Directive (RED), which stated that by 2020, 20% of the EU's consumed energy should be generated with renewable sources [80]. This target was achieved and even surpassed, with a total share of 22%. Sweden, Finland and Latvia are the leading countries, with more than 40% of their total consumed energy coming from green sources. In addition, of the total amount of generated green electricity, 36% corresponds to wind energy [81].

On the one hand, the onshore European market in 2021 was led by Germany, followed by France, UK and Sweden. It signified a 27% of the global onshore installations and the number of new installations increased in 20% from 2020 to 2021. The shares per country of newly installed onshore capacity in 2021 are shown in Figure 9a. In the European territory, these installations are characterized by a large dispersion, which is represented by the fact that 55% of the new installations correspond to other non-leading countries.

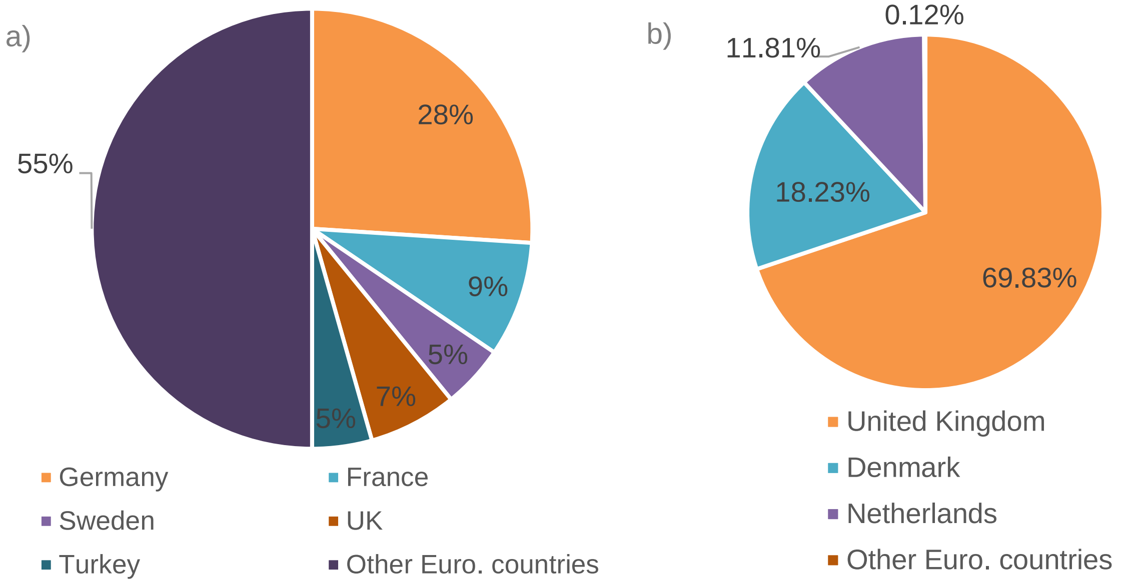

Figure 9 Shares of a) onshore b) offshore, newly installed capacity. They correspond to the WT strength of European countries in 2021. Ref.: [24]

On the other hand, considering the cumulative European offshore installed capacity, the leaders are the UK (21.9% world share), Germany (13.5%), the Netherlands (5.3%) and Belgium (4%). The offshore European market increased in approximately 3 GW of new capacity in 2021. Its shares by European country are presented in Figure 9b. The leading countries of offshore new installations are the UK, accounting for nearly 70% of the total, followed by Denmark and The Netherlands.

Since 2009, the UK had the highest global number of offshore total installed capacity, but the Global Wind Energy Council (GWEC) reported that China surpassed it by the end of 2021 [24]. The case of the UK is particularly important as it holds seven of the ten world biggest offshore wind farms. The factors that arouse the UK's status are mainly geographical: the country is surrounded by vast sea areas, with a long coastline which facilitates access to it, a

Figure 10 Hornsea 2 wind farm in the UK, with 1.3 GW capacity. Ref.: [83]

shallow seabed and good wind speed and frequency, which overall benefit the installation of immense wind farms [82]. The latest record installation was announced in 2022, when the world's largest windfarm started operating at complete service: the Hornsea 2. This 1.3 GW offshore farm was installed by Ørsted, which will allow powering over 1.4 million UK homes [83]. An image of this project is presented in Figure 10 [83].

2.3.3. Future perspective for the European market

To keep on working towards a more sustainable future, the European Green Deal was approved in 2020 [1]: a set of proposals for making Europe the first climate neutral continent in the world and reducing at least 55% of the greenhouse gas emissions by 2030, as well as becoming carbon neutral by 2050. In particular, the EU set a dedicated strategy for onshore [84] and offshore renewable energy [85]. For instance, considering that the total installed offshore wind capacity in 2021 was 28.2 GW, the EU's strategy aims to increase it until 60 GW in 2030 and 300 GW by 2050, which represent a multiplying factor of 2.1 and 10.6 over the current generation, respectively [85].

This strategy not only covers energy production factors (such as grid infrastructure and energy potential of sea basins) but also diverse issues such as sea accessibility, research transfer into business, international cooperation, employment aspects and supply chain strength.

Concerning future technological standards, the main concerning factor around WT material supply lays in permanent magnets (PM): an expensive and metal intensive component. Even though their use will be diminished in onshore applications [86], in the case of offshore turbines the shift will be less straight forward. It is challenging to find an alternative solution to PM that copes with the increasing size and capacity of offshore WT, as well as keeping them light and of low maintenance [35].

According to a JRC analysis, three future estimations can be proposed for WT material demand in 2050: low-, medium- and high- demand scenarios. Each of them contemplates different market shares for every WT technology, giving a considerable relevance to the GB-SCIG technology in the low-demand case, whereas assuming an almost DD-PMSG monopoly in the high-demand one. In all the cases, the steepest increase in material demand is foreseen in the following decade, whereupon the market will follow a more stable tendency [16].

As a consequence, these projections have a major influence in the predicted increase in the commodities' demand. For example, in the case of offshore wind, the JRC has predicted that by 2050 the amount of Mn and Ni used in 2018 could be multiplied by 6 - 6.5. The structural material that shows a highest boost is Cu, for which a factor of 8 is expected in a high-demand context. In the case of technology-specific materials (such as B, Dy, Nd, Pr and Tb), the current required absolute amounts for the offshore technology are higher than in the onshore one because of the use of PM. However, the ratio in the onshore case is higher because the future increase in offshore material demand is proportionally less intense than the onshore one.

Two key material future trends should be pointed out as well. Firstly, material efficiency will keep on improving. This means that the relative material input per unit of capacity will keep on decreasing (less materials will bring more energy capacity). Secondly, there is a future trend towards more lightweight materials. According to a study developed by McKinsey [87], steel will be substituted by high-strength steel (HSS) and Al and carbon fibre usage will be promoted, therefore, influencing the future material ratios in WT.

Comparing future requirements with the material supply, it is concluded that to pursue the EU green energy strategy, Dy, Nd and Tb will face supply issues and their current available quantity will be mainly used for WT [16].

Summing up, as already pointed by the European Green Deal, there will be a clear increase in wind energy, and this will require a proportional rise in the material requirements: their appropriate amount and in their right ratio. This rise is due to an increase in the number of WT, in addition to a growth in the WT capacity and size, as it has been taking place during the last 30 years [88]. An evaluation on whether the supply chain of each of the WT materials will bear such an increase in demand is a pending question.

2.4. Methods for the management of material flows

2.4.1. Industrial Ecology

Industrial Ecology (IE) consists of a multidisciplinary study of industrial and economic systems, their linkages with fundamental natural systems and how they can become more eco-compatible. It brings together ecology, economics, engineering and thermodynamics [89]. The term has its origin in the 1970s, as Japanese researchers aimed at reducing system's extreme dependency on resources [90].

Some decades later, meaningful insights were added to the IE concept. Frosch and Gallopoulos [91] stated that humans should manage industrial systems in the same way as natural systems work: waste from a species / process should be used as a resource for another, closing the loop. The envisioned modern Industrial Ecosystem is presented in Figure *11*, where the core of these interconnected processes is defined with four pillars: material extraction, processing / manufacturing, consumption and waste management.

This new theory aimed at matching outputs with inputs, so unnecessary raw materials (limited resources) and pollution could be avoided, and waste treatment processes could be reduced (limited waste). Therefore, this visualization of the technological processes as part of the biosphere could bring not only ecological advantages but also economical, because the efficiency of the system is increased. IE is characterized by four main statements: it is proactive not reactive (promoted by industrial concerns), it is designed-in not added-on (because it affects the design of the whole value chain), it is flexible not rigid, and it is encompassing not insular, meaning that it covers several industrial sectors as well as countries and cultures [92].

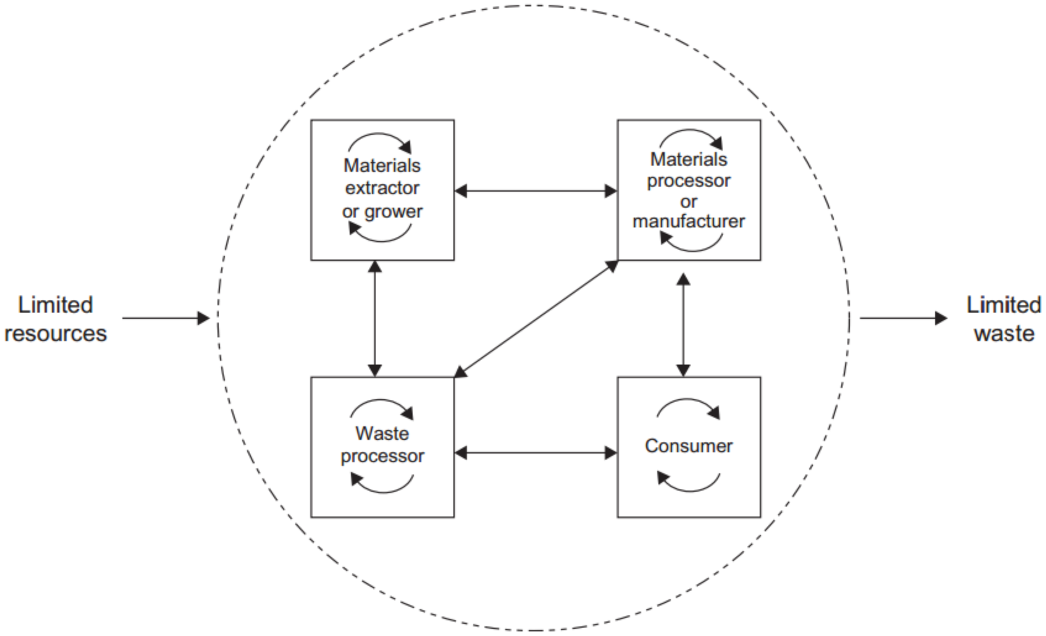

Figure 11 Model of the Industrial Ecosystem [89].

As a necessary progression, some analytical tools were identified for making IE possible. Some examples are design for the environment (DfE), life cycle assessment (LCA) and material flow analysis (MFA), among others [89][93]. DfE consists of the (re)design of products with the aim of reducing their environmental impacts, while LCA is a methodology that quantifies the resources' use and emissions per unit of product or service. It can cover the whole value chain from material extraction (cradle) until the disposal and/or recycling (grave) of the components. Several system boundaries are used depending on where should be the focus of the study and in order to compare different scenarios [94]. For example, an LCA of a product can be performed in two different countries (geographical boundaries) to do a comparative analysis afterwards.

Due to the importance of material balances, a central methodology of IE is MFA, which quantifies the flows of materials that are used, reused, stored and lost in a certain industrial metabolism [2] with particular temporal and spatial boundaries. One of the first published MFA was that of Frosch et al. [91] for a global platinum group cycle in 1989. Since then, industries have been increasingly acknowledging the usefulness of this tool because it helps identify the bottlenecks and inefficiencies of material flows in the economy. In addition, an MFA is the starting point to get the information for the inventory analysis in an LCA, and ultimately assess the impacts of the product or service. In recent years, global MFAs for specific metals have become a must to operate efficiently and for a variety of purposes [95]. A detailed definition of MFA is presented in the following subsection.

2.4.2. Material Flow Analysis

Material Flow Analysis (MFA) consists of the collection, modelling and analysis of data describing the flows of materials in and out of an economy from sources to sinks [96]. Its scale can cover a global industrial system or a national or even local one, and it is based on mass balancing. MFA can bring a complete picture of resource flows and stocks through the economy, take into account their direct and indirect effects in the social and environmental context and show how these flows vary between countries / industries [97]. They can cover a variable level of detail and completeness.

In MFA, the term material refers to both substances and goods. A substance is any (chemical) element or compound composed of uniform units, all of identical composition, thus homogeneous. Goods are made up of one or several substances and refer to merchandise and wares. The terms “product” and “commodity” are usually used as synonyms of “goods” [98].

A process is defined as transformation (anthropogenic or natural), transport or storage of materials. In each of them the material balance is verified in order to match the inputs and outputs of the system. During transportation processes, goods are not transformed but just relocated over a certain distance.

Besides goods and processes, the systems boundaries should be defined as well. They are the ones between the investigated elements and others in space and time. They should be defined in temporal terms, i.e. time span over which the system is investigated and balanced; as well as in spatial terms, i.e. geographical area in which the processes are located.

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[2] Industrial metabolism comprises the processes to which materials and components are subjected in industrial ecosystems.

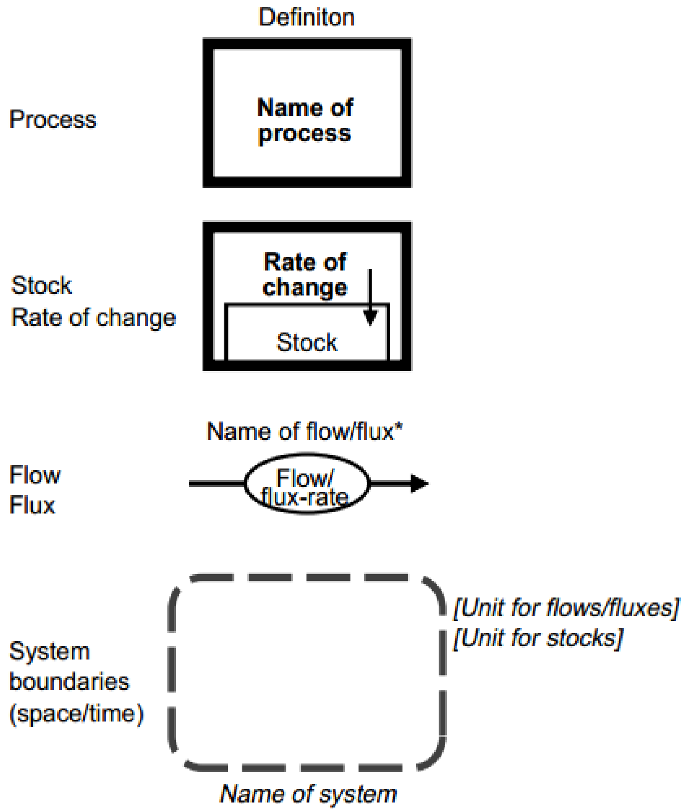

Figure 12 Main symbols used in MFA diagrams [98].

MFA studies always require a diagram that represents the analysed system, the object of investigation. Sankey diagrams are usually employed, in which flows are represented with arrows, with the flow value indicated and a width proportional to the amount. This makes the whole diagram more visual and the analysis more straightforward. In Figure *12* the symbols of each of the elements of an MFA diagram are presented [98]. As shown, processes (both transformation and transport) are symbolized by rectangular boxes. A "black box" approach is used: processes within the box are not taken into account and just the input and output flows and the stock are of interest. A smaller box within the "process" box symbolizes the stock, which is the cumulative difference of flows in and out of that process. Both the stock's value and its annual addition are typically incorporated.

MFA can be static if it describes a system or region in a particular moment, or dynamic, when the system is studied over time. In this case, in-use and "hibernating" stocks over a certain period are taken into account [95]. In addition, the temporal boundaries can be of a past situation, in which case a retrospective MFA is performed, or of a future scenario, with a prospective MFA [99]. Some other particular types of MFA have emerged, such as the MaTrace, a model that can trace the fate of materials in open-loop recycling, taking explicit consideration of losses and the quality of scrap into account [100]. Among MFA models, Material System Analysis (MSA) is of particular relevance [101] and will be explained in the following section. In a recent approach, MSA was applied for a multilayer analysis, which will be described in detail in subsection 2.4.2.2.

2.4.2.1. Material System Analysis

The Material System Analysis (MSA) method is an MFA model and it consists in the analysis of flows and stocks along the supply chain of particular selected raw materials or semi-finished goods [102]. The main goal of MSA is to serve policy needs or support industry decisions for raw materials and to monitor the circular economy implementation, among others [101]. It was particularly developed for the EU to support its material regulations [97].

MSA is based on mass conservation as the main principle to quantify stocks and flows along the 7 defined life cycle stages: exploration, extraction, processing, manufacturing, use, collection and recycling. It also takes into account the reuse, loss and disposal of materials along the lifecycle, as well as the remaining materials in tailings, products in use and landfills. In each stage, it considers the trade of materials, i.e. the inputs and outputs of the material cycle boundaries.

As end-of-life pathways, several possibilities are considered: disposal (which includes landfill), functional recycling (further sent to processing, to manufacture or exported), or non-functional recycling. The latter refers to material which is collected and incorporated in an associated large-magnitude material stream, where the original function is not required or where it acts as contaminant. The material is dissipated in the technosphere and it is difficult to recover it. Therefore, the properties that made the material preferable in the first place are reduced or lost [103], [104] [105].

Another relevant aspect is that the MSA is applied for a specific region (geographical boundaries) and time (temporal coverage), which should be maintained throughout the whole analysis [102].

This methodology was launched by the EC in 2015 within the context of the European Raw Materials Initiative (RMI) [106]. The project aimed at analysing the flows of relevant materials through the European economy, considering their whole life cycle. The initial study focused on 28 raw materials, which has been further enlarged until 33; including Al, Cu, Mn and Ni, among others [97] [107] [108]. Numerous bottlenecks and hotspots within various value chains have been identified, presenting an opportunity to strengthen supply chain resilience and seize opportunities through targeted actions. As an example, in the case of Co, Li, Mn, NG and Ni study [107], it was detected a clear potential development of recycling of old scrap, with a rate of 0% in some cases.

2.4.2.2. Multilayer Material System Analysis

The Multilayer Material System Analysis consists in performing an MSA for several commodities with the same system boundaries and overlapping them to deduce synergies and bottlenecks in the whole system. The flows and stocks of each commodity are analysed in general terms (whole market), as well as for the chosen technology and, in more detail, in each application or subtype. Therefore, this method allows the analysis of the linkages between the individual raw materials and the supply chain they are part of.

Matos et al. [109] developed and used this model defining five different layers:

1. "Grandparent" layer, which covers the flows and stocks of the technology as a whole.
2. "Parents" layers, which correspond to the distinction of each application or subtypes.
3. "Child" layers, which focuses on the MSA of the different commodities (raw materials) in each of the applications or subtypes analysed in the "parents" layers. The same commodities should be chosen for each of the applications/subtypes. This is the layer with highest detail of the whole study.
4. Each of the commodities is analysed from the point of view of the whole technology.
5. The MSA of each of the raw materials in the whole market is also necessary.

Once each layer is obtained, the multilayer perspective facilitates an analysis that takes into consideration their interconnectedness. For instance, when examining the raw materials in a specific technology and application (child layer), it is crucial to take into account whether similar challenges are encountered in the whole market for that raw material, whether those drawbacks are exclusive to that technology, and other relevant factors. Therefore, decisions can be made that address the root cause of the issues.

Matos et al. [109] applied a multilayer MSA for Li-ion portable batteries (LIB), with an EU28 scope for 2016. To do so, four main LIB applications were selected: portable electronics (portable PCs, cell phones, tablets, etc.), electrical mobility (battery electric vehicles, plug-in

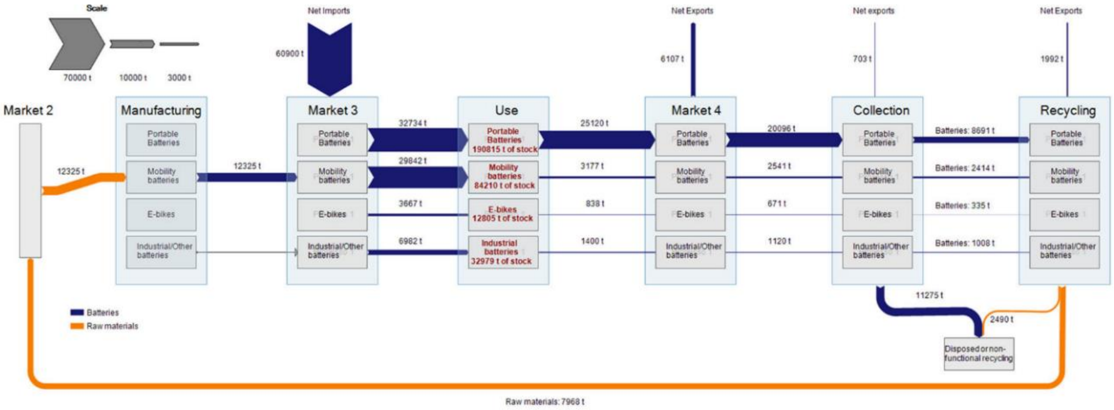

Figure 13 Sankey diagram showing the flows of the whole Li-ion battery cycles, differentiating the four applications [109].

hybrid electric vehicles, etc.), e-bikes and industrial batteries (excluding mobility). These market applications determine the chemistry of the battery and, therefore, their material content. Five raw materials were analysed: cobalt (Co), lithium (Li), manganese (Mn), natural graphite (NG) and nickel (Ni). These commodities were selected for their criticality level in terms of economical importance and availability, as well as for their representativity in the defined applications. Each of these choices define the layers of the analysis, as depicted above [109].

In Figure 13 the flows throughout the whole LIB cycle are shown, capturing the information of the “grandparent” and “parent” layers [109]. As it can be noted, the most massive flows and stocks correspond to portable and mobility batteries. An insight that arises from these results is that the collection strategies of LIBs should become more efficient, especially for portable batteries which present a high accumulation in hibernating in-use stocks. In the case of Li, this analysis and the obtained conclusions are of particular importance because LIB is its main application, while this is not the case for the rest of raw materials. This study unveiled a necessary coordinated strategy throughout the different life cycle stages at the EU in order to boost the European manufacturing capacity and competitiveness. For example, Co, Ni and Mn can be refined at battery grade levels within the EU. However, this is not the case for Li and NG, which can become critical points and one of the main supply bottlenecks. All this obtained knowledge can be used for proper policy making and coherent business decisions.

2.5. Material Flow Analysis of wind turbine materials

To analyze the state of the art of MFA for wind turbines, two main sources have been used: *ScienceDirect* and *The Web of Science* and the number of results in each case are presented in Figure *14*.

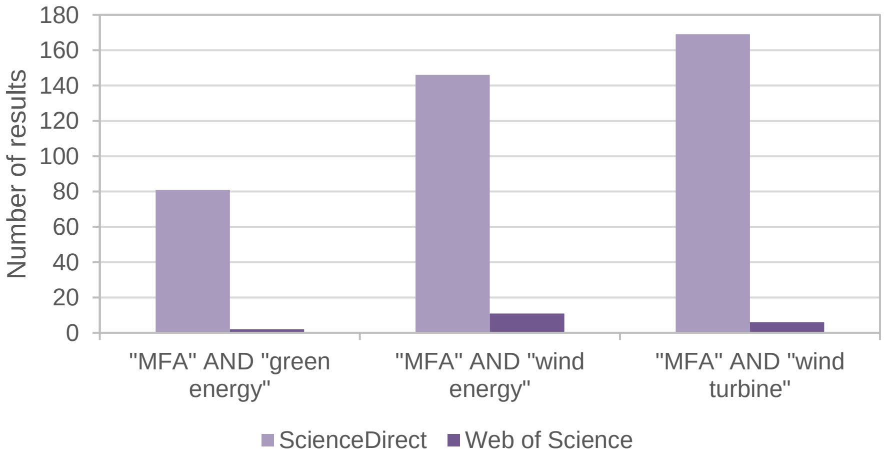

Figure 14 Number of results for each of the searches in each searching tool.
Note that MFA was used with the whole wording.

First of all, looking for MFA about "green energy" provided 81 results in *ScienceDirect* and just 2 in *The Web of Science*. When looking for MFA about wind energy, around 150 results are obtained with *ScienceDirect* and 11 with *The Web of Science*, 6 of them coinciding between both databases. The highest number of documents were obtained when looking for MFA about "wind turbines", almost 170 in *ScienceDirect*, probably because it is a much more generally used concept. In *The Web of Science*, 6 results were found, three of them coinciding with the previous search. It should be noted that the term MSA with both wind energy and wind turbine, brought really few or no results. Therefore, it is concluded that this type of methodology is applied in fewer studies.

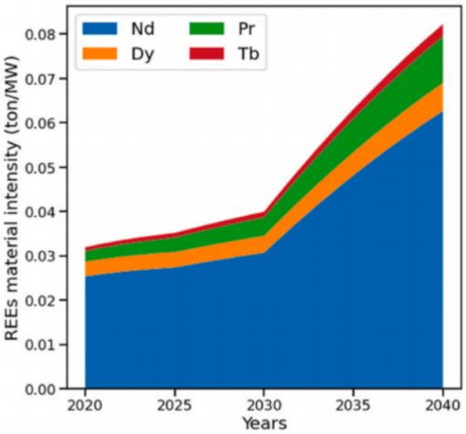

Figure 15 REE material intensity changes in WT from 2020 to 2040. Ref.: [42]

Diving into some insights from wind turbines MFA studies, firstly an initial selection of materials and their content in WT should be stipulated (an overview of this has been presented in section 2.1.4). However, there is a lack of analysis showing the exact composition in each of the parts and types. Meaningful results are shown by Li et al (2022) [42], with the composition of each raw material in each part of the turbine and for each type of technology; but not many research like this can be found. Figure *15* shows some results of the Li et al. prospective MFA, in which it was found that REE intensity will be doubled from 2030 to 2040, basically because PM-based generators will be replacing PM-free nacelles [42].

Secondly, the uptake of wind energy in the examined region should be known, as well as the installed (in-use stock) and flows for each type of WT [110]. Some of the studies are developed in non-European countries such as China [111][112] and even though the terminology is the same, the applied methodology might encompass some differences with European studies [110]. Other relevant concepts are the lifetime, maintenance during the usage phase (replacement of some parts) and End-of-life assumptions.

Summing up, a clear gap is present in the study of WT from the broad European perspective. From a methodology point of view, another clear gap is the application of Material System Analysis, almost non-existent for this particular case. Therefore, multilayer MSA is also a method that remains to be applied.

3. OBJECTIVES

Considering the economic interest towards the development of the wind energy sector [31], is of utmost relevance to understand which is the magnitude of the material flows related to wind turbines, their composition and their dependence on the types of drive-train system. In this line, the **general objective** of this master thesis is to analyse the EU's supply chain flows and stocks of materials in the wind turbine industry as a whole and for selected raw materials.

To achieve the general objective, the following specific objectives are defined:

1. Assess the circularity of these flows by studying the trade, losses, and end-of-life pathways of the technology. The analysis also includes the evolution of the wind sector since its starting point and how this affects the current material cycle.
2. Reveal the dependency of the technology on the material's availability and circulation in the EU. Therefore, the flows and stocks of some critical specific materials in wind turbines are analysed. Taking into account their strategic economic importance, their role in the wind turbine structure and the data availability, the selected materials are nickel (Ni), manganese (Mn) and neodymium (Nd).
3. Detect possible bottlenecks in the supply chain of these specific materials, by linking the results in the wind turbine context with their material flows in the rest of applications. This should be considered by policymakers when managing the vital resources needed in the EU industry and when designing societies that aim at being as circular as possible.

From a methodological point of view, another specific objective is to show how the multilayer Material System Analysis can be applied in the case of wind turbines and to demonstrate the interest of such approach for this technology.

4. METHODOLOGY

4.1. Material System Analysis: stocks and flows estimation

The Material Flow Analysis (MSA) developed in this thesis encompass the lifecycle boundaries excluding extraction and processing stages, as applied by Matos et al. [109]. The phases that were included are manufacturing, use, collection, end-of-life and recycling. The nomenclature stablished in BIO by Deloitte in 2015 [97] and further revised in 2020 [113] was utilized throughout the study. The list of parameters (i.e., flows and stocks of material) that are included in each MSA is presented at the beginning of this thesis. Each parameter was characterized by a code containing a letter (corresponding to the life cycle stage) and a number. This nomenclature is used along the following sections.

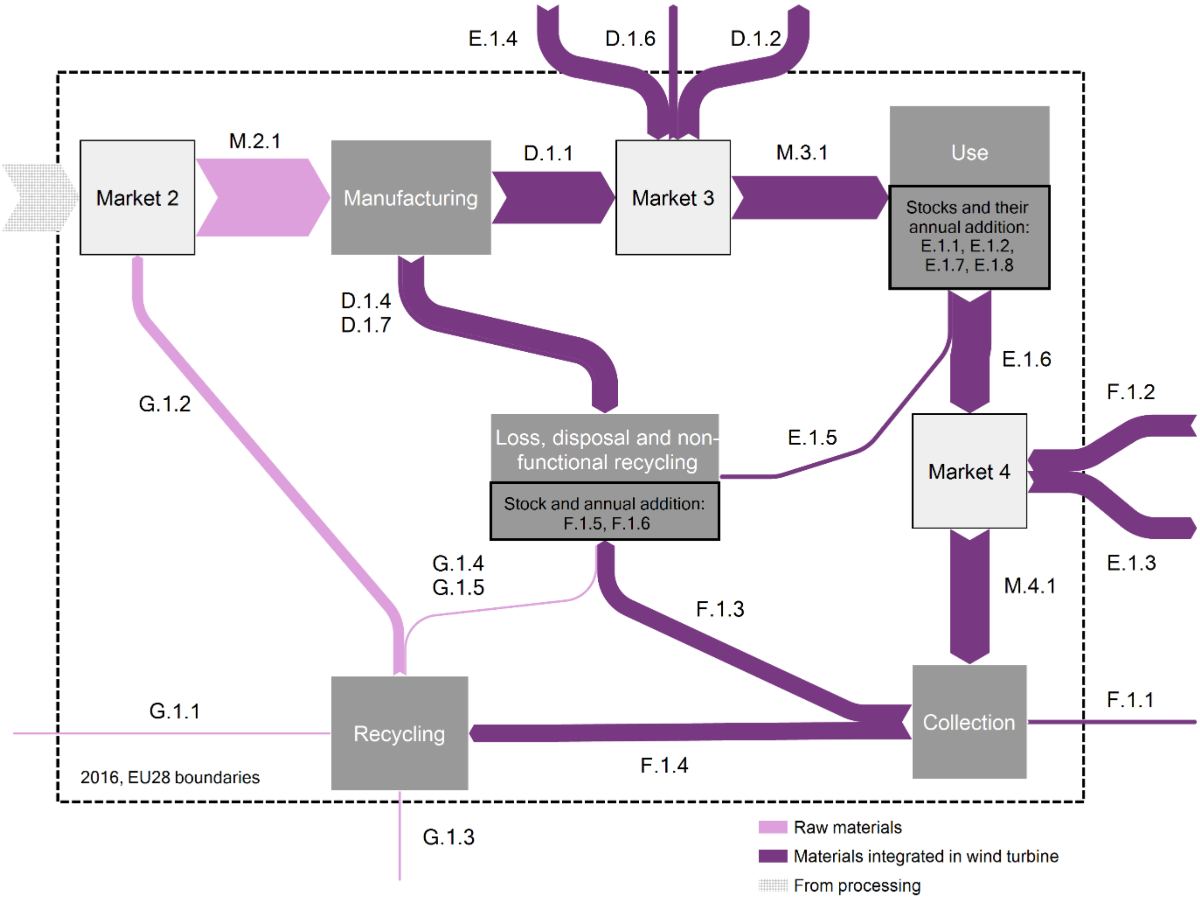

Figure 16 Sankey diagram of the generic Material System Analysis, with the parameters included in this study. Light purple: raw materials; dark purple: materials already embedded in a wind turbine component. The dotted flow represents the material coming from the previous part of the life cycle (from processing).
Note that the arrows' width in this case is just illustrative and does not correspond to any numerical result.

All the obtained data and results were visually depicted in a Sankey diagram for each layer. In Figure 16, a reference scheme shows the connections between each of the flows, life cycle stages and markets. A distinction was made between two types of material flows: the lighter color represents flows of raw material and the dark color corresponds to material already embedded in a wind turbine component. At the top left of Figure 16 the dotted flow represents the material coming from the previous part of the life cycle (from processing). In addition, this study distinguishes Market 2 (defined as the one between processing and manufacturing), 3 (between manufacturing and use) and 4 (between use and collection). The introduction of the "market stages" concept emerged from the revised MSA specifications [113] as a solution to address challenges arising from the presence of re-exports, which refers to materials that are imported and subsequently exported without undergoing additional processing.

Apart from the flows, the diagram also includes the stocks of material in use (E.1.1), at end-of-life (E.1.2, inside use box) and in landfill (F.1.5, disposal box); as well as the annual addition to each of these stocks (E.1.7, E.1.8 and F.1.6, respectively). Note that the aforementioned stocks correspond to cumulative stocks, hereinafter simply identified as stocks.

The stocks and flows were calculated through a set of equations, which are described in the following subsections. Some of them were obtained from the original methodology developed in BIO by Deloitte [97] and some from peer-reviewed articles [114], in order to adapt the calculations to the available data.

4.1.1. Manufacturing phase

The manufacturing phase refers to the production of wind turbines. The first flow that was calculated is the quantity of material in manufactured wind turbines sent to use (M.3.1). This flow comprises two components: one which corresponds to newly installed wind turbines, and a second one for the components that need replacement in older turbines due to failure.

On one hand, the amount of material needed for the new wind turbine installations was estimated from their material intensity, the market shares of each type of WT and the installed wind capacity in the analysed year. The calculation proceeds as follows:

$$M_{T,n} = \sum [I_k \cdot MS_{k,n}] \cdot C_n \tag{1}$$

where *n* is the analysed year (temporal boundary), $M_{T,n}$ is the total material requirement (in metric tons, t) in year *n*, I_k is the intensity of materials in a particular type of wind turbine *k* (in t/MW), $MS_{k,n}$ is the market share (in percentage) of the type of turbine *k* installed in year *n* and C_n is the capacity addition installed during year *n* (in MW). In this case, the summation covers the different types of drive-train systems *k* in turbines, which are specified in subsection 4.4.1.

On the other hand, the inflow of material required for the repaired and replaced components was calculated. This stream is a worst-case scenario of the failure of wind turbines. For each WT component *j*, data on its failure rate per year and per turbine (FR_j) is needed, as well as its material intensity. The first was directly obtained from the literature. Then, to calculate the material intensity, a model which relates the mass of the component with the rotor diameter was applied. It has been previously used by studies such as Sieros et al. [115] and Caduff et al. [116] and it considers the following equation:

$$\log M_j = \log a + \log D \cdot b \tag{2}$$

where M_j is the mass of the component *j* (in t), *a* is a constant factor, *D* is the rotor diameter (in meters) and *b* is a scaling factor.

The failure rate as well as the mass of each component are defined per wind turbine unit. Therefore, the last required parameter to calculate how much is collected due to component replacement was the amount of wind turbines that on average have been installed in the EU in all history until the analysed year n (N_T). This value is estimated by dividing the cumulative installed capacity in year n (C_T, in MW) by the average nominal power of one WT ($P_{ave.}$ in MW). This average is obtained with a weighted calculation, by considering the nominal power each year (P_m, in MW) and the corresponding newly installed capacity on that year (C_m, in MW). The calculation for the N_T is expressed in the following equation:

$$N_T = \frac{C_T}{P_{ave.}} = \frac{C_T}{\sum_{n-L_{use}}^{n-1}\left[\frac{P_m \cdot C_m}{C_T}\right]} \tag{3}$$

Note that in the summation, *m* varies from the first year when current wind turbines were installed ($n - L_{use}$) until one year before the studied year n (i.e., $n - 1$). Wind turbines installed during these years contain the components that could be replaced in the analysed year n.

Finally, the flow M.3.1 can be calculated as follows:

$$M.3.1 = M_{T,n}\ (eq.1) + \sum\left[M_j(eq.2) \cdot N_T(eq.3) \cdot FR_j\right] \tag{4}$$

where the summation covers each of the components *j* that should be replaced in year *n*.

Following with the estimation of parameters of the Sankey diagram (Figure 16), the trade flows express the imports and exports from EU of manufactured products, i.e. E.1.4 and D.1.2. This data was directly obtained from the literature.

Therefore, to calculate the material flow of manufactured products (D.1.1), a material balance was applied, represented in Figure 16 and expressed in the following equation:

$$D.1.1 = M.3.1 + D.1.2 + D.1.6 - E.1.4 \tag{5}$$

where D.1.6 correspond to exports of manufacturing waste (directly obtained from literature).

The waste that is generated in the manufacturing phase and sent to disposal (D.1.4) was calculated by knowing the share of each material *i* lost during the production of wind turbines with respect to the flow of manufactured products ($W_i(\%)$). The following equation was used:

$$D.1.4 = \sum\left[D.1.1 * \frac{I_i}{I_T} * W_i(\%)\right] = \sum\left[D.1.1 * \frac{I_i}{\sum I_i} * W_i(\%)\right] \tag{6}$$

where I_i and I_T correspond to the material intensity (in t/MW) of each material *i* and of the total wind turbine, respectively; and $W_i(\%)$ is the share of material *i* that is sent from manufacturing to disposal and considered waste. The summations are over the different materials *i*. With all this information, the material amount sent to manufacturing (M.2.1) was calculated as follows:

$$\mathrm{M.2.1} \;=\; \mathrm{D.1.1} - \mathrm{D.1.4} - \mathrm{D.1.7} \tag{7}$$

where D.1.7 is the output from the value chain at the manufacturing step (directly obtained from literature), i.e., the manufacturing losses.

A second way to calculate the flow M.2.1 is by knowing the number of wind turbines that were manufactured in the analysed year n ($N_{manuf.n}$, obtained from the literature) and multiplying it by the material intensity (I_k) and the mean nominal power (P_n). The material needed for repairing works must be added as well. The total calculation is shown in the following equation:

$$\mathrm{M.2.1} \;=\; \sum I_k \cdot P_n \cdot N_{manuf.n} + \sum \left[M_j(eq.2) \cdot N_T(eq.3) \cdot FR_j\right] \tag{8}$$

Note that the number of wind turbines and the mean nominal power correspond to the analysed year n. The first summation is over the materials *k* in wind turbines and the second one over the components *j* that should be replaced in year *n*. The results of both calculation routes are compared in section 5.4.

4.1.2. Use phase

In the use phase, the stock of manufactured products (E.1.1) was calculated in the same way as the flow of material in newly installed wind turbines, but in this case by applying the cumulative capacity installed until the studied year *n* and the mean market share of each wind turbine technology *k* applied throughout history. Therefore, equation (*1*) was applied to calculate E.1.1, with *n* being all years since the beginning of wind energy history until the studied year.

Three of the parameters in this phase were directly obtained using the equations in BIO by Deloitte's report [97]. They depend on a series of product rates. The stock of manufactured wind turbines at end of life (E.1.2) is dependent on the rate of product kept by users after the end of life (R_{eol}), the exports of manufactured products to reuse (E.1.3) are dependent on the rate of product exported for reuse (R_R) and the in-use dissipation (E.1.5) is dependent on the in-use dissipation rate of the product (R_D). The corresponding equations are shown below:

$$\mathrm{E.1.2} \;=\; (\mathrm{D.1.1} + \mathrm{E.1.4}) \cdot \frac{1}{(1+AG)^{L_{use}}} \cdot \left[\frac{1-\left(\frac{1}{1+AG}\right)^{L_{eol}}}{1-\frac{1}{1+AG}}\right] \cdot R_{eol} \cdot (1 - R_D) \tag{9}$$

$$\mathrm{E.1.3} = (D.1.1 + E.1.4) \cdot \left(\frac{1 - R_{eol}}{(1+AG)^{L_{use}}} + \frac{R_{eol}}{(1+AG)^{L_{use}+L_{eol}}}\right) \cdot (1 - R_D) \cdot R_R \tag{10}$$

$$\mathrm{E.1.5} = (\mathrm{D.1.1} + \mathrm{E.1.4}) \cdot R_D \tag{11}$$

where AG is the annual growth rate of wind turbines manufacturing, L_{use} is their lifespan and L_{eol} is the time during which the product (in this case wind turbine) is kept by the users.

The calculation of the amount of material that arrives at end of life and is collected for treatment (E.1.6) is explained hereafter. This flow consists of two parts: the material of wind turbines that, upon reaching their end of life, are completely decommissioned; and the material of the damaged components that should be replaced. Note that the first part of the flow (decommissioned material) can be calculated by using equation (*1*) and the second part (failed components) has already been explained in the manufacturing phase (subsection 4.1.1).

To sum up, the calculation was done applying the following equation:

$$\mathrm{E.1.6} = \left(\sum I_k \cdot MS_{k,n-L_{use}}\right) \cdot C_{n-L_{use}} + \sum \left[M_j(eq.2) \cdot N_T(eq.3) \cdot FR_j\right] \qquad (12)$$

where the first part corresponds to decommissioned wind turbines and the second to failed components. Therefore, the first summation is over the types of drive-train systems *k* and the second one is over the different turbine components *j* that must be replaced. It should be noted that in this case, the assessment of market shares ($MS_{k,n-L_{use}}$) and wind turbine capacity ($C_{n-L_{use}}$) was conducted for the year ($n - L_{use}$), which corresponds to the year when the installation of the wind turbines being decommissioned in the year n occurred.

Following, the annual addition to in-use stock of manufactured wind turbines (E.1.7) can be calculated whether by subtracting the material at end of life collected for treatment from the material inflow to use (E.1.7 = M.3.1 - E.1.6); or by using equation (*13*), defined in BIO by Deloitte's report [97].

$$E.1.7 = (D.1.1 + E.1.4) \cdot \left(1 - \frac{1}{(1 + AG)^{L_{use}}}\right) \cdot (1 - R_D) \qquad (13)$$

The results of both calculation routes are compared in section 5.4.

Finally, the annual addition to end-of-life stock of manufactured wind turbines (E.1.8) was calculated with the following equation, defined in BIO by Deloitte's study [97]:

$$E.1.8 = (D.1.1 + E.1.4) \cdot \frac{1}{(1 + AG)^{L_{use}}} \cdot \left(1 - \frac{1}{(1 + AG)^{L_{eol}}}\right) \cdot (1 - R_D) \cdot R_{eol} \qquad (14)$$

4.1.3. Collection phase

The collection of materials at end-of-life (EoL) phase analysis starts with the flows of exported (F.1.1) and imported (F.1.2) products, directly obtained from the literature.

With this, the outflow from Market 4 (M.4.1), which corresponds to the products at EoL that stay in the studied market for treatment, was calculated applying the following mass balance:

$$M.4.1 = E.1.6 + F.1.2 - E.1.3 - E.1.5 \qquad (15)$$

After collection, the end-of-life material gets divided into the one towards disposal (F.1.3) and the one to recycling (F.1.4). The flow to disposal covers the landfilled material as well as the incinerated one, while the flow to recycling contains the fully recycled material and the non-functionally recycled one. To do so, the flows coming from M.4.1, representing decommissioned wind turbines and component failures, were disaggregated into the different materials *i* that comprise WT (Fe, Zn, Cu, Al, etc.). Then, the following equations were applied:

$$F.1.3 = \sum M_i \cdot S_{i,landfill} + \sum M_i \cdot S_{i,incineration} \tag{16}$$

$$F.1.4 = \sum M_i \cdot S_{i,funct.recy.} + \sum M_i \cdot S_{i,non-funct.recy.} \tag{17}$$

where $S_{i,landfill}$, $S_{i,incineration}$, $S_{i,funct.recy.}$, $S_{i,non-funct.recy.}$ are the shares of each material *i* that go to each end-of-life pathway (percentage in landfill, incineration, functional and non-functional recycling respectively). Note that M_i is the amount of material *i* (in t) contained within M.1.4 and the summation is performed over the different materials *i*.

Following, the stock in landfill (F.1.5) was calculated by using equation (*18*), defined in BIO by Deloitte's study [97].

$$F.1.5 = (Flow\ to\ landfill) \cdot \left(\frac{1-\left(\frac{1}{1+AG}\right)^{L_{use}}}{1-\frac{1}{1+AG}} \right), \tag{18}$$

with $Flow\ to\ landfill = D.1.4 + F.1.3 + G.1.5$

Note that in this case the incinerated material is already included in F.1.3, therefore the ashes and emissions produced are considered as part of the landfill as well.

Finally, the annual addition of material to stock in landfill (F.1.6) was calculated with the material balance expressed by equation (*19*).

$$F.1.6 = D.1.4 + F.1.3 + G.1.5 \tag{19}$$

4.1.4. Recycling phase

The last stage is recycling, comprised by 5 parameters. The most straight-forward to obtain flow is the secondary material from non-functional recycling (G.1.4) which corresponds to the second part of equation (*17*). Therefore, it was calculated as follows:

$$G.1.4 = \sum M_i \cdot S_{i,non-funct.recy.} \tag{20}$$

The exports of secondary material from post-consumer recycling (G.1.3) were estimated similarly to D.1.4, in this case by knowing the share of each secondary material *i* exported after recycling (ESM_i). The following equation was used:

$$G.1.3 = \sum \left[(F.1.4 - G.1.4) * \frac{I_i}{I_T} * ESM_i \right] \tag{21}$$

where I_i and I_T correspond to the intensity (in t/MW) of each material *i* and of the total wind turbine, respectively; and $ESM_i(\%)$ is the share of exported secondary material *i* from post-consumer recycling. The summation is over the different materials *i*.

Another crucial parameter is the recycling waste that is sent to disposal (G.1.5), determined by employing the end-of-life recycling rate (EoL-RR) of each individual material. The EoL-RR is defined by Matos et al. [109] and is presented in equation (22) for a particular material *i*, along with the material balance that derives from the MSA (right part of the equation).

$$EoL - RR_i = \frac{G.1.1_i + G.1.2_i + G.1.3_i}{M.4.1_i} = \frac{F.1.4_i - G.1.4_i + G.1.5_i}{M.4.1_i} \tag{22}$$

Therefore, the recycling waste amount was calculated as follows:

$$G.1.5 = \sum [(EoL - RR)_i \cdot M.4.1_i + G.1.4_i - F.1.4_i] \tag{23}$$

Finally, the secondary material from functional recycling that is sent to manufacturing (G.1.2) closes the loop and was obtained by material balance using the following equation:

$$G.1.2 = F.1.4 - G.1.3 - G.1.4 - G.1.5 \tag{24}$$

The flow of secondary material that is sent to processing (G.1.1) is obtained from the literature. Two last calculations should be performed to complete the needed data for the Sankey diagrams. One is the verification of the mass balance at the use step, which corresponds to the fulfilment of the following equation:

$$D.1.1 + E.1.4 - E.1.3 - E.1.5 - E.1.6 = E.1.7 + E.1.8 \tag{25}$$

Finally, the material from processing to Market 2 was calculated from subtracting (M.2.1 – G.1.2) and is represented with a dotted arrow at the Sankey diagram (Figure 16).

4.2. Multilayer assessment for wind turbines

With the presented methodology for the MSA completion, this thesis is based on a multilayer MSA analysis. As presented in section 2.4.2.2, several layers should be defined for the analysis, which in this case were specified as follows:

- “Grandparent” layer: flows and stocks of the entire wind turbine technology. This layer contains all the information about wind turbines’ materials, market, trade, technology types, etc. Unit: kilo metric tons (kt).
- “Parent” layer: for this specific work, this layer is defined according to the different types of drive-train systems in wind turbines, i.e., gearbox and direct drive. Unit: kt.
- “Child” layer: it consists of the MSA of selected materials for the study, in this case nickel (Ni), manganese (Mn) and neodymium (Nd). Unit: metric tons (t).
- MSA of selected raw materials in the whole technology, therefore Ni, Mn and Nd in wind turbines (which is basically aggregating the results of the previous layer).
- MSA of the selected raw materials in the market (for all applications). This layer is used as a reference to compare the supply chain behavior of the selected materials in the wind turbines to the market in general, with the same system boundaries.

Figure 17 is a schematic representation of the methodology applied in the wind turbines case study, offering a visual depiction of all the layers under analysis.

Overall, the data was coming from secondary sources (e.g. Farina et al. [114] and Shammugam et al. [117]) because there was no direct contact with the industry to perform the analysis. However, some restricted data from the Joint Research Center (JRC) of the European Commission was accessed [118].

The MSA of the last layer was directly obtained from the work of Ciacci et al. [55], [67] and the rest of the layers were developed by the author of this thesis following the methodology described in the previous section.

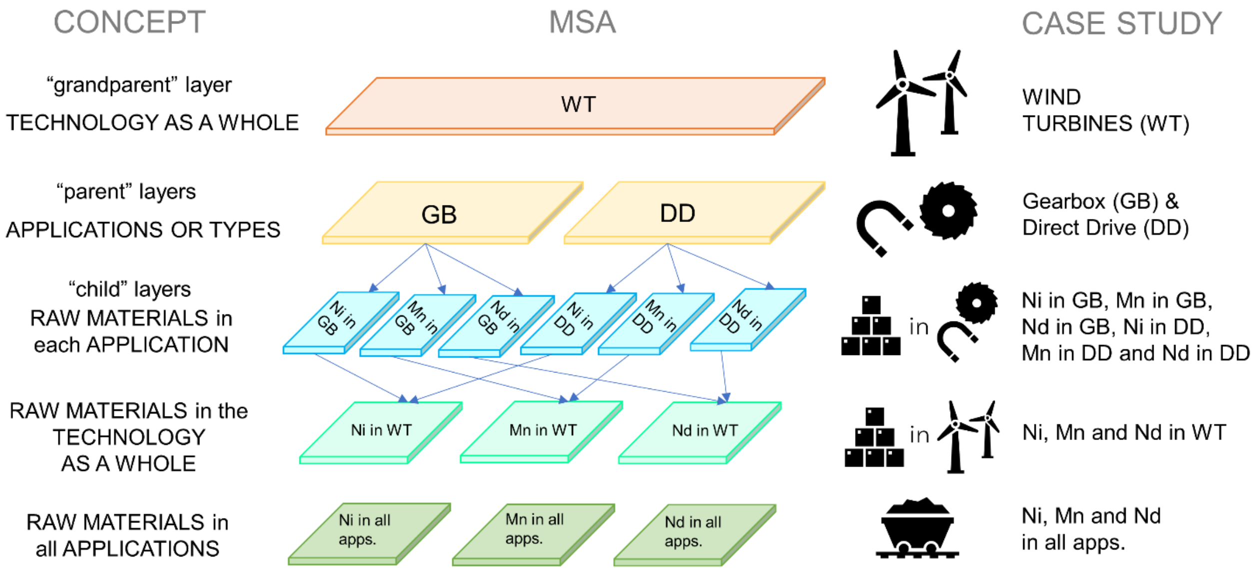

Figure 17 Schematic representation of the multilayer Material System Analysis methodology.

4.3. System boundaries: geographical, temporal and technological coverage

The current study presents a multilayer MSA of wind turbines in the EU-28[3] for the year 2016. Therefore, in all the previously presented equations, n is equal to 2016.

The specific year was chosen due to the highest availability in data, mainly regarding the MSA of the specific materials in all applications. This determined the geographical boundaries as well, which had to include the United Kingdom, as it was a member of the European Union at that time [119].

From a technological point of view, as introduced in the previous section, it was decided to separate the wind turbines in types of drive-train systems, that is, gearbox (GB) and direct-

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[3] EU-28 includes Belgium, Denmark, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, United Kingdom, Austria, Finland, Sweden, Cyprus, Czechia, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Slovakia, Slovenia, Bulgaria, Romania and Croatia [119].

drive (DD) (parent layer of Figure 17), due to the differences in material composition that they present. This composition was not considered dependent on the location where the wind turbine is installed (onshore and offshore). Hence for example an onshore double-fed induction generator (DFIG) was considered to have the same material composition (mass % of each material) as the same type of generator in an offshore wind turbine and in wind turbines of different sizes. This assumption is applied as well in other studies such as the published article of Shammugam et al. [117].

Regarding material boundaries, among all the substances discussed in the literature review pertaining to wind turbines, this analysis excludes concrete, which is exclusively utilized in the foundations and the connecting part with the tower. The focus of this work is on the diversity and criticality of materials included in the Wind Turbine Generator (defined as the ensemble tower, rotor and nacelle [79]), which is installed and disassembled separately from the foundations [120]. This final component constitutes a significant portion, comprising more than 75% [114] of the total weight of the installation. In onshore turbines, it predominantly consists of concrete, while in offshore turbines it is a combination of steel and concrete [117]. Therefore, it is not included to maintain the focus on the complexity of the rest of components. This approach has been followed by other studies on wind turbine materials, such as by Jensen et al. [121] and by Carrara et al. from the JRC [8]. However, a brief discussion about the foundations' material is included in the results section.

4.4. Data sources and data gaps

4.4.1. Manufacturing phase

Firstly, the amount of material in manufactured wind turbines sent to use in the EU (M.3.1) was calculated with equation (*4*). The part of the calculation that corresponds to the newly installed wind turbines requires data on the installed wind capacity in 2016 and on market shares of each drive-train system. The considered specific technology types were Squirrel Cage Induction Generator (GB-SCIG), Wound-Rotor Induction Generator (GB-WRIG), Double-Fed Induction Generator (GB-DFIG), Permanent Magnet Synchronous Generator (both GB-PMSG and DD-PMSG) and Electrically Excited Synchronous Generator (both GB-EESG and DD-EESG). Note that gearbox (GB) and direct drive (DD) types are differentiated. The turbine capacity and market shares were obtained from the JRC Wind Energy Status Report [122]. The total European wind capacity used in this work is 160.2 GW. The historical evolution of the market shares was available just until 2015. Therefore, to estimate the values for 2016, a weighted average between 2014 and 2015 was performed, as it was done by Ciacci et al. [67] in their study on secondary Nd sources.

From a composition point of view, the material intensity of the wind turbine was obtained from Farina et al. [114]. This publication compiled the data from journal articles, life cycle assessment reports and the Ecoinvent database [123], [124] from 1991 until 2016 and they normalized all the data per t/MW.

To estimate the material needed for the replaced components and due to their complexity and variety, only the parts with highest failure rates, as presented by Carroll et al. [125]–[127] and Shammugam et al. [117], were considered. These are pitch, gearbox and yaw. In addition, the incorporation of generator failures was necessary due to the criticality of the generator's material, specifically the presence of REEs. Three types of failures were considered: minor repairs, major repairs and major replacements [126]. Each failure type involves the replacement of a different mass percentage of the WT component, namely 10%, 20% and 100% respectively. These considerations provide the material requirements for the repairing works that must be taken into account in the MSA [117]. In addition, it was assumed that on the decommissioning year there is no additional material demand from maintenance [117]. The data of failure rates per year and per turbine of the selected components is presented in Annex 8.1.

In the failure rates study, an important concept is the bathtub curve, which represents the general change trend of the failure process during the whole life cycle. It is divided in several stages: an infant mortality region (early high failure), a steady state (stable operation with low failure) and a wear-out region (high failure in the last years of operation) [128]. This curve can be observed in Figure *18*. Due to a lack of more complete data, the rates used for the analysis were considered to correspond to the steady state region, with no temporal variation during the life cycle [117]. Some authors argue that failure rates may increase due to marine conditions [129], therefore offshore WT are subject to higher early failures [130]. However, these considerations were neglected in this master thesis.

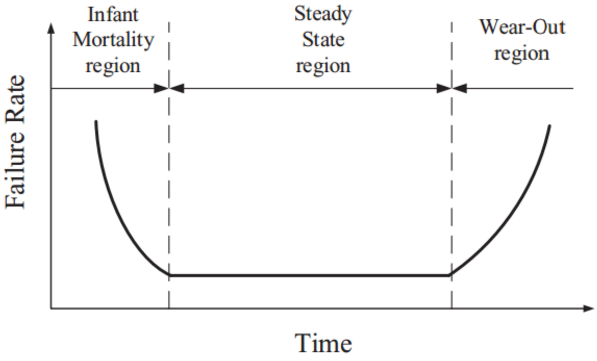

Figure 18 The bathtub curve. Ref.: [128]

On the other hand, to estimate the material intensity of the failed components, the modelling factors for each component were obtained from Shammugam et al. [117] (presented in Annex 8.2) and the rotor diameter *D* taken as reference was 100 m [29].

The data on nominal power of wind turbines and installed capacity per year was obtained from the JRC Wind Energy Status Report 2016 [29], with which the total number of wind turbines was calculated using equation (*3*). Note that in this case, *n* varies from 1996 (the first year when there is wind energy installation) until 2015 in the summation. The wind turbines installed in these years are the ones that contain components that could be replaced in 2016.

To apply equation (*4*) and obtain the flow M.3.1, the only additional remark is that components *j* correspond to pitch, yaw, gearbox and generator.

Trade data (imports and exports) is present in EUROSTAT [131] in monetary unit (€), corresponding to the PRODCOM number (PRCCODE) “28112400: Generating sets, wind-powered” [132] [133]. To get this data in mass unit (the desired one for this analysis), the above-mentioned PRCCODE was translated to the Harmonized Commodity Description and Coding System (HS) [134]. Therefore, the HS code 850231 was used to get the amount of material imported (E.1.4) and exported (D.1.2). The manufacturing waste exported outside EU (D.1.6) was considered negligible due to a lack of data.

Following, the waste produced in the manufacturing stage and sent to disposal (D.1.4) is estimated by considering steel, glass/carbon composites and zinc cycles. This assumption was valid because more than 79% of the total material in the wind turbine is steel-related, more than 7% is glass or carbon composite and almost 5% is zinc [16]. The share of each of these three materials sent as waste from manufacturing to disposal ($W_i(\%)$) was obtained from literature on their respective EU material cycles [135][136][137][138].

The output from the value chain at the manufacturing step (D.1.7) is considered zero due to a lack of data. Note that there might be waste that is reprocessed inside the manufacturing plant itself [139], which is out of the scope of this analysis.

Another way to calculate the processed material that goes to manufacturing (M.2.1) was by applying equation (*8*). The number of manufactured wind turbine units was obtained from EUROSTAT [131], using the PRODCOM number 28112400. This data was transformed into the amount of material with the material intensities from Farina et al. [114] and the nominal power from the JRC Wind Energy Status Report 2016 [29].

4.4.2. Use phase

For the calculation of material that enters the use phase, it was assumed that the material intensity of each type of wind turbine does not change with time [114] and that finished products enter the use phase in the same year of production.

A market analysis of the wind capacity installed since 1996 until 2016 was performed, with the annual shares of each drive-train system obtained from the JRC Wind Energy Report 2016 [29] and the installed wind capacity of each year from the Global Wind Energy Council Reports 2007, 2013, 2015 and 2016 [122], [140]–[142]. The values are presented in the Annex 8.3.

Regarding the end-of-life of wind turbines, according to a report from WindEurope about wind turbine decommissioning [120], the Building Law regulates that wind turbines, with their auxiliary facilities and access roads, are to be dismantled within one year of the final cessation of use. Therefore, it was estimated that no wind turbine material stays at its location for more than one year at the end-of-life and all the corresponding material is collected within that year. This means that the rate of product kept by users after end-of-life, R_{eol}, is zero, resulting in both the stock E.1.2 and the annual addition to stock E.1.8 being zero as well.

Concerning the use of the turbine, it was assumed that no material dissipation takes place, and that there is no re-use of the wind turbines. Therefore, rates R_D and R_R were estimated as zero, as well as their corresponding parameters (E.1.5 and E.1.3).

The average lifetime of a wind turbine was complex to evaluate because its industry is still relatively young [40]. However, it was assumed as 20 years for onshore wind turbines and 25 years for offshore ones, reported by WindEurope [120] and Carrara et al. [16]. Therefore, the equipment that is totally dismantled in 2016 is the one from onshore wind turbines installed in 1996 and the offshore machinery installed in 1991. It has been reported by WindEurope that exactly in 1991 the world’s first offshore European wind farm was installed, so the total newly installed offshore capacity was less than 5 MW [143]. The material associated to this is considered negligible in comparison to 1 GW of onshore newly installed in 1996 (which also gets decommissioned in 2016). Hence in equation (*12*), $n - L_{use}$ is equal to 1996.

Note that throughout wind energy history, some specific wind farms may have been decommissioned before their lifetime in the so-called repowering projects. These refer to the complete or partial dismantling and replacement of turbine equipment to get technological advancements, economic gains and increase the profit of the plant [144][145][146]. The material associated to these projects is not taken into account in this analysis due to a lack of predictability on the frequency in which the upgrades have been carried out.

4.4.3. Collection phase

The flow of materials that are exported (F.1.1) and imported (F.1.2) at the end-of-life was considered zero in the case of wind turbines, as stated in several other studies [147] [111]. In addition, there is increasing regulation on shipment of waste outside the EU and the recycling and treatment of the material at end-of-life is enhanced inside the territory.

Therefore, the assumption was coherent [148]. In the case of our analysis, as E.1.5, E.1.3 and F.1.2 were considered negligible (as explained above), the flow M.4.1 coincides with the flow E.1.6 (applying equation (*15*)). After the collection, the end-of-life material towards disposal (F.1.3) and to recycling (F.1.4) is obtained by following the scheme presented in Figure *19*.

The decommissioned wind turbines' material was divided in flows for the tower, the rotor and the nacelle, using the mass estimation described by equation (*2*) and the modeling factors presented in Annex 8.2 [117]. Along with the parts that reached failure (pitch, yaw, gearbox and generator), the flow is further divided into 6 main materials: low alloyed steel, high alloyed steel, iron and cast iron, copper, aluminum and others; using the mass percentages presented by Shammugam et al. [117]. An intermediate portion of electrics and electronics is segregated into low alloyed steel, copper, aluminum and others by using the composition published by Charitopoulou et al. [149].

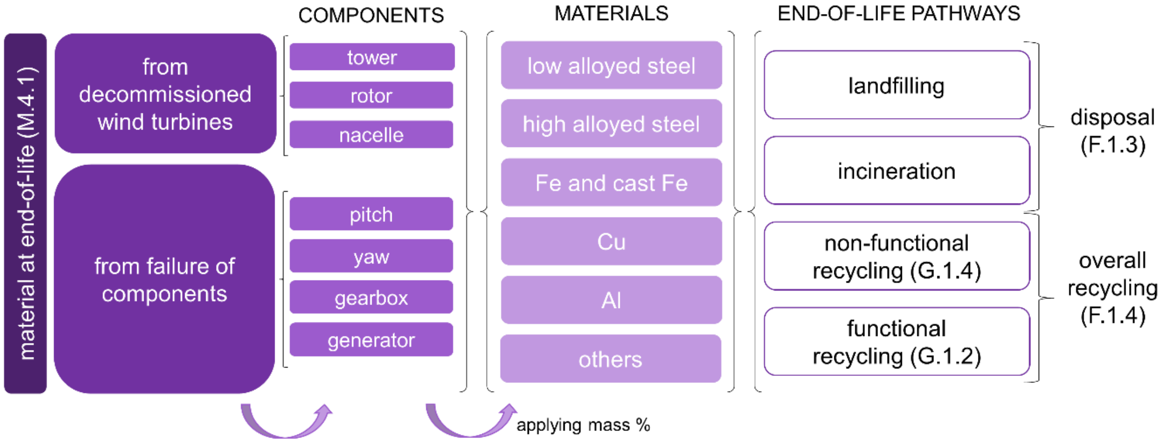

Figure 19 Scheme of the material classification from an aggregated flow to the different components and materials until the considered end-of-life pathways.

Once the amount of each material was obtained, the shares going to the four end-of-life pathways were accessed in Demuytere et al. [150] and Eygen et al. [151]. Different shares were assigned depending on the type of material and on whether it is in the nacelle or in other turbine components. The considered four end-of-life possibilities (as shown in Figure *19*) were landfill (disposal, F.1.3), incineration (also considered disposal [152], F.1.3), non-functional recycling (downcycling [103], G.1.4) and functional recycling (G.1.2).

4.4.4. Recycling phase

The flow of material from post-consumer non-functional recycling (G.1.4) was directly obtained with equation (*20*), and the same assumptions and data sources that were used to calculate F.1.4 are applied in this case. The calculation of material exports from the EU of secondary material from post-consumer recycling (G.1.3) was estimated just in the case of steel, which corresponds to almost all the material present in the flow (the exact amount of steel is presented in section 5). The share of steel that arrives at end-of-life and that is traded to outside the EU (ESM_{steel}), i.e. exported, was obtained from a material flow analysis for the EU28 steel cycle in the literature [135]. This share was directly multiplied by the amount of steel that arrives at the recycling phase to get G.1.3 (equation (*21*)).

The secondary material that is sent to processing (G.1.1) was considered to flow directly to manufacturing as part of G.1.2 as it was not considered remarkable either in the study by Matos et al. [109]. Another relevant parameter is the recycling waste that is sent for disposal in the EU (G.1.5). This flow was also estimated just for the case of steel and by using the parameter end-of-life recycling rate of the steel cycle ($((EoL - RR)_{steel})$), which is 76% corresponding to secondary sources [135].

4.4.5. Raw materials layers

To acquire the raw materials layers, in most of the cases the calculations were performed similarly to the methods presented in the previous subsections but applying the corresponding concentration of Ni, Mn or Nd [16]. However, some specifications should be made.

With the reference MSA presented at the beginning of this section (Figure 16), in the child layers the flows D.1.6, D.1.7, E.1.3, E.1.5, F.1.1, F.1.2 and G.1.3 are considered zero. In most of the cases, this assumption is corroborated by the MSA studies of Ni, Mn and Nd by Ciacci et al. [55], [67], where the flows D.1.6, D.1.7, E.1.5 and F.1.2 are also assessed as negligible. For the flow F.1.1 (exports at end of life) the amount of material of the MSA in all applications that is exported is less than 0.2% of the products that arrive at end of life, so it is also considered negligible in the case of wind turbines.

For the flow E.1.3 (exports for reuse), as it was explained for the case of wind turbines as a whole, it is not a usual practice to reuse the wind turbine in another site, so the amount is considered negligible as well. Finally, in the case of G.1.3, no data was found on the trade of these materials coming specifically from the wind turbine application.

At the end-of-life, Ni and Mn were assessed as the rest of steel-related components [55], while Nd is non-functionally recycled, as reported by Yang et al. [70], Rizos et al. [153] and Dias et al. [28]. No incineration is considered in the raw materials layers.

The obtained in-use stock quantities are compared to the amount of these materials in all market applications, through the data published in several articles of Ciacci et al. [55], [67].

4.4.6. Additional methods

The Sankey diagrams presented along this master thesis were created with the *e!Sankey* software by the author. In addition, *Excel* and *PowerPoint* were also used for the design of some Figures. Moreover, for the improvement of some parts of the written text, *ChatGPT* was employed. The only intention behind using this tool was to review and clarify some sentences that were previously written already by the author.

5. RESULTS AND DISCUSSION

5.1. “Grandparent” layer

5.1.1. General analysis

Figure *20* depicts the EU28 wind turbine flows and stocks in 2016, corresponding to the “grandparent” layer of the multilayer assessment. Raw materials’ flows are represented in light blue arrows while a distinction was made for the flows of material already embedded in wind turbine components, in dark blue. The unit of all the values is kt.

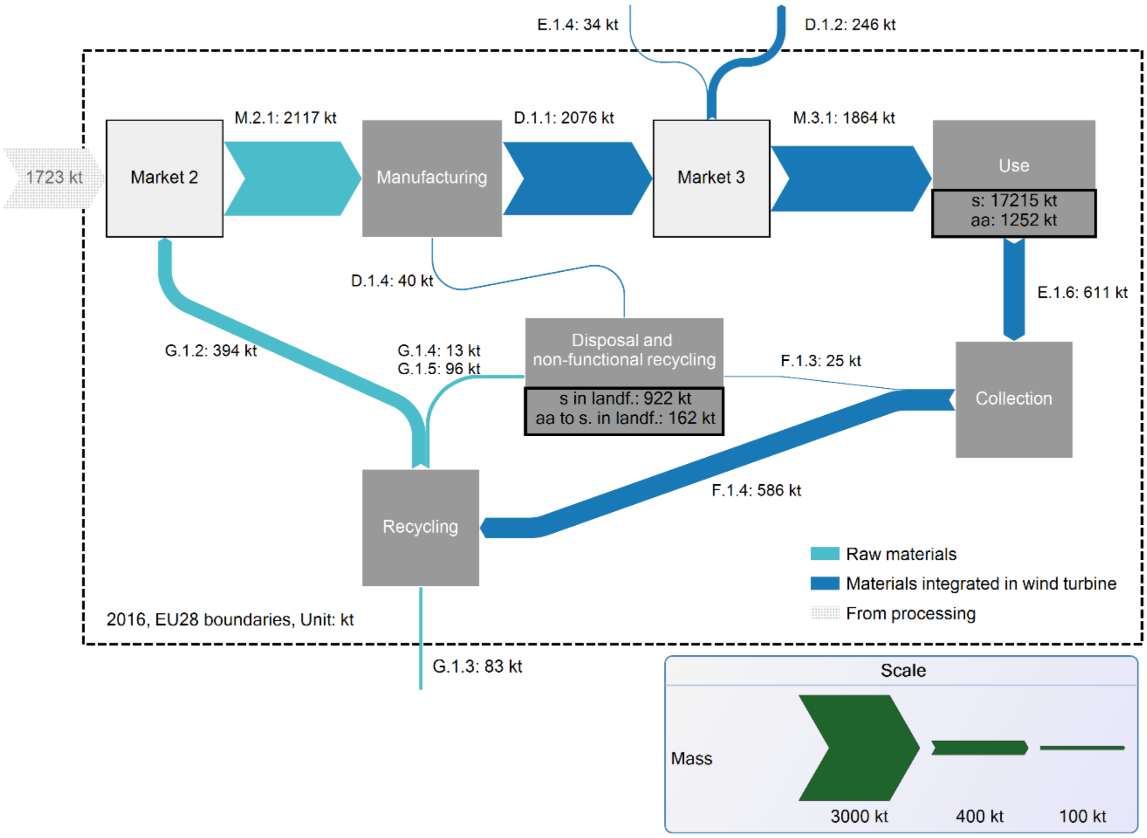

Figure 20 Flows and stocks of the whole wind turbine material cycle. The flows in light blue correspond to raw material and in dark blue to material already integrated in wind turbine components or assemblies. The dotted flow represents the material coming from the previous part of the life cycle (from processing). The abbreviations “s” and “aa” correspond to stock and annual addition to stock, respectively. Note that in the case of end-of-life (central box) the stock and annual addition refer to the ones in landfill (without considering non-functional recycling).
Differences of 1 kt can be encountered due to approximations.

In general, if Figure 20 is compared with the reference Sankey diagram of in the methodology part (Figure 16), it can be noted that in the “grandparent” layer the flows D.1.6 (manuf. waste exports), D.1.7 (manuf. losses), E.1.3 (reuse exports), E.1.5 (in-use dissipation), F.1.1 (exports at EoL) and F.1.2 (imports at EoL) are considered negligible. In addition, the flow M.1.4 (products at EoL collected for treatment) is not visualized either because it is assumed that no trade of products takes place in Market 4 (connecting use and collection phases).

Therefore, the flows E.1.6 and M.1.4 are equal and just the former is represented in Figure *20*. This is also the reason why Market 4 is not displayed either in the diagram.

In the case of the stocks (in the scheme as "s") and annual additions (as "aa") in the use phase, the material that arrives at end-of-life and that is kept by the users is considered negligible. Therefore, the values presented in the diagram inside the use phase correspond to E.1.1 (stock of in-use products) and E.1.7 (annual addition to in-use stock). It should be noted that the annual addition to in-use stock accounts for 7.3% of the total stock of wind turbines in operation, serving as an indicator of the growth that this technology is experiencing.

From a quantitative point of view, the width of the arrows in the diagram is proportional to the amount of material that they represent, for which the scale can be observed at the bottom right of Figure *20*. A visual analysis readily reveals that most of the material is contained in the section of the cycle from Market 2 until the use phase. The greatest flow is at the top left of the cycle and corresponds to the processed material sent to manufacturing with a value of 2117 kt. This is the amount of material that enters the studied cycle.

To analyse how much material is kept in the life cycle in each phase and how much is traded or lost, the values presented in Table 3 were calculated from the results of Figure 20. In the manufacturing phase and market 3, most of the material is retained in the cycle (around or more than 90%), which is an appropriate sign for assuring EU's supply security. In the use phase, the amount of material at end-of-life that is collected for treatment is a low share (33%) of the total material that arrives to the use phase. The main reason of this is that the wind turbine sector in 2016 was growing. In 1996 there were 12 times less newly installed wind turbines than in 2016, therefore in 2016 there were much more new wind turbines than the ones that were decommissioned. Finally, in the collection and recycling phases, 96% and 67% (respectively) of the material is kept in the cycle and the rest is disposed, non-functionally recycled or traded.

Table 3 Share of material retained in each phase of the cycle in the EU system.

Phase which keeps material	Flows that are divided	Share of material kept in the cycle (resulting quotient, in %)
Manufacturing	D.1.1 / M.2.1	98.1%
Market 3	M.3.1 / D.1.1	89.8%
Use	E.1.6 / M.3.1	32.8%
Collection	F.1.4 / E.1.6	95.9%
Recycling	G.1.2 / F.1.4	67.3%

Diving into the material composition, as shown in Figure 21, the flow M.2.1 is composed in a 73.8% of steel and iron, 9.2% of glass and carbon composites and 6.4% of zinc, as main

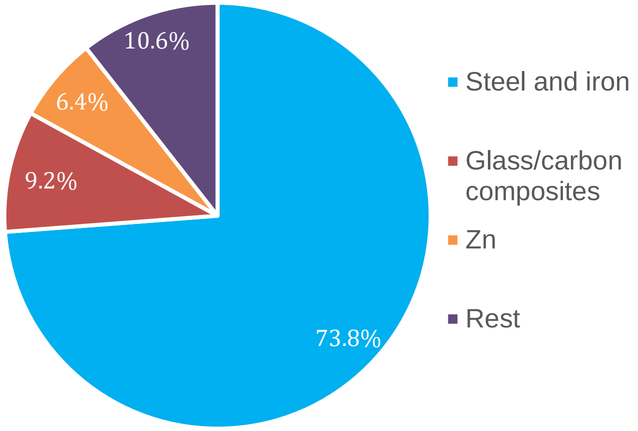

Figure 21 Composition of the flow of processed material sent to manufacturing (M.2.1) in mass percentage.

elements. Therefore, these are the three materials that were considered relevant for the estimation of manufacture waste (as explained in subsection 4.4.1).

Considering the rest of materials, WT contain 8 strategic or critical raw materials: REE, boron, silicon metal, manganese, nickel, copper, niobium and aluminium. This is the lowest number of different CRM compared to other renewable energy technologies such as batteries (9 CRM), electrolysers (20 CRM) and solar PV (11 CRM) [8]. A less diverse composition allows a smoother management of resources, so that the efforts in achieving a higher circularity, better recyclability and stronger supply can be focused in a more concentrated range of materials.

The composition of the flows at the end-of-life is presented in subsection 5.1.4, along with their linkage with the EoL pathways and recyclability. A more in-depth comparison of these results with the specific ones for Ni, Mn and Nd is presented in section 5.3.

The in-depth analysis and discussion of the results obtained for each phase are presented in the following subsections 5.1.2, 5.1.3 and 5.1.4, and a reflection about the data uncertainty and additional comments are given in section 5.4.

5.1.2. Manufacturing phase and Market 3 analysis

A clear outcome of the results is that EU28 is a globally predominant manufacturer of wind turbines and related components. Just 1.8% of manufactured products in 2016 were imported from outside the EU28 (flow E.1.4 in Figure *20*), mainly United States (55%), China (25%) and Aruba (10%) [131]. Thus, there are no significant external dependencies in terms of material mass quantity that can be identified in this context. This result is confirmed by the JRC, who published a supply chain analysis of wind turbines. The study confirmed that the EU is responsible for 24% of wind turbine component manufacturing worldwide. It includes the fabrication of the nacelle casing, blades, gearbox, tower, shafts, among others. The EU also accounts for 18% of WT assemblies, which mainly corresponds to the power generator finishing. The share increases to 34% when considering super assemblies, which represents the completion of the whole turbine [8]. Considering that 23% of the global wind turbine new installations in 2016 took place in the EU28 [122], and along with the JRC analysis, it can be confirmed that the EU28 had the industrial capability to provide for itself with wind turbine manufactured components, minimizing the imports.

Concerning the exports, around 12% of the manufactured components are traded to countries outside the EU (flow D.1.2 in Figure *20*), mainly Turkey, United States, Australia, Canada, Egypt, Mexico and South Africa, as reported by Eurostat [131]. However, most of the components manufactured in the EU stay in it for their subsequent use. Indeed, 5 out of the top 10 manufacturers in the world are from the EU and they collectively correspond to a market share of 42% globally [4].

5.1.3. Use phase analysis

For the use phase, it is estimated that 17215 kt were accumulated as stock of material embedded in the wind turbine sector. This amount is 54 times higher than the stock in use or hibernating of Li-ion batteries in 2016 in the EU (321 kt), as reported by Matos et al. [109]. A similar comparison can be done with solar photovoltaics. The International Renewable Energy Agency (IRENA) published that in 2016 the cumulative mass of solar photovoltaic panels present in in-use stock was 1405 kt [154][155], that is 12 times lower than in the case of wind turbines. From this it is concluded that wind turbines are a prominent potential source of future recycled raw materials, in a magnitude greater than that of LIB and solar photovoltaics. Other low-carbon power generation technologies, such as hydropower, biomass and nuclear, have comparatively low mineral requirements, therefore the need for material securing and recovering is less urgent [156].

This discussion is of uttermost relevance as well for future considerations. The International Energy Agency (IEA) has reported that to meet the Sustainable Development Scenario (temperature rise of max. 2ºC as stated in the 2015 Paris agreement [157]), the mineral demand by 2040 for clean energy technologies will be 4 times higher than the one in 2020 [158]. The highest material increase is led by electric vehicles and battery storage systems but among clean energy production technologies, wind turbines represent the steepest boost in demand, closely followed by solar PV [158]. To meet these requirements is of high interest to target the stock materials as a possible future source.

5.1.4. Collection and recycling phases analysis

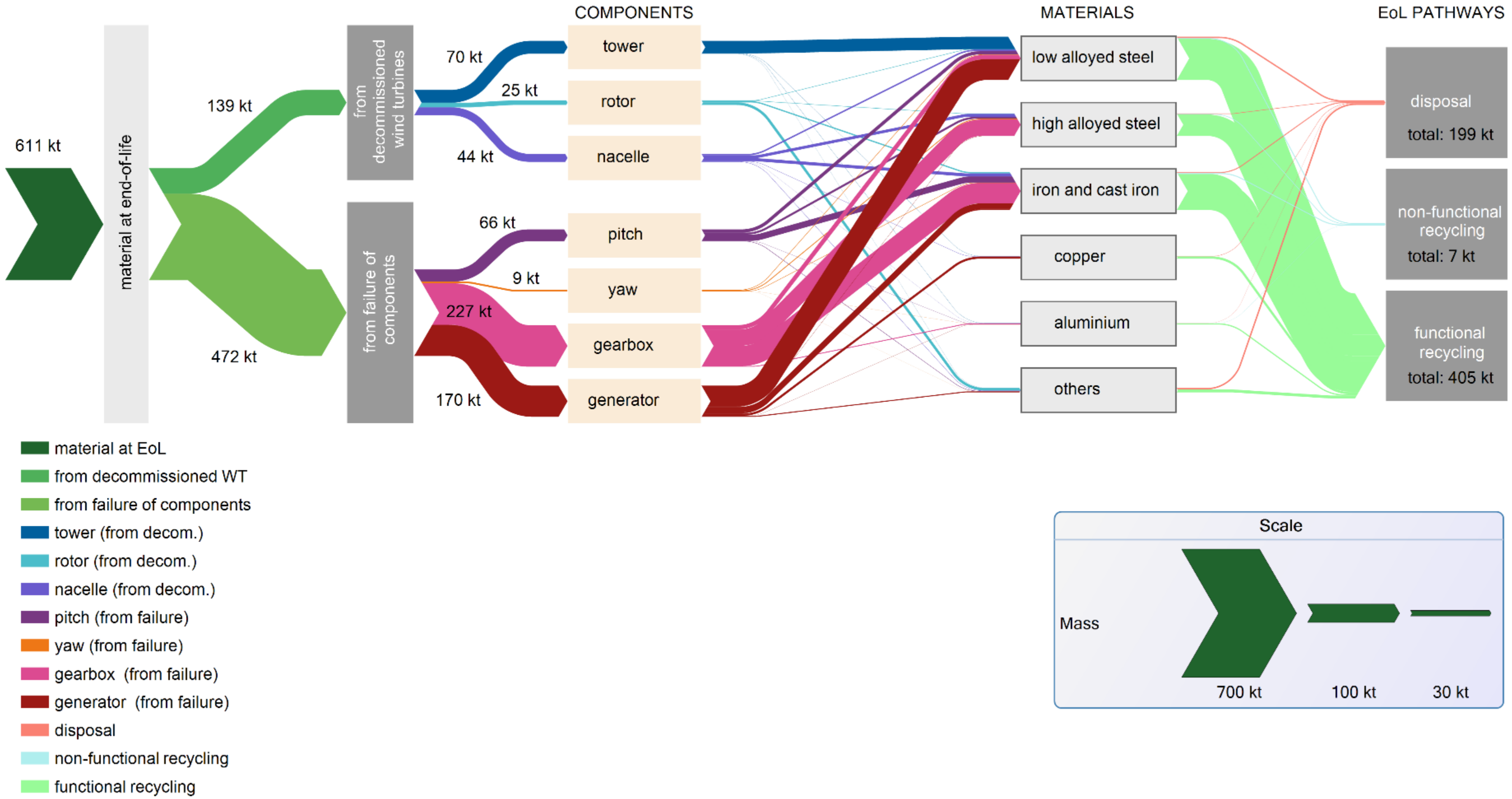

Figure *22* Classification of the flow that arrives at the end-of-life into the different wind turbine components, kind of materials and EoL pathways.

A diagram with the classification of the EoL flow into the different components, materials and possible final pathways is presented in Figure 22. The total material that is collected at end-of-life had two origins: decommissioned wind turbines and failed components. They can be further divided in 7 different components and, each of them, in 6 different materials. These are then allocated in each of the final pathways: disposal, non-functional recycling and functional recycling.

The materials from wind turbines that are fully decommissioned correspond to 22.7% of the total end-of-life material flow (E.1.6), the rest being the material needed to repair or replace components that reach failure. This difference in the amount of material between both parts of the flow is mainly due to the low amount of WT that got decommissioned in 2016, because of the few new installations of 1996 (just 1 GW of capacity). In addition, it should be noted that the material for maintenance works might have been overestimated, as it assumes a constant failure rate throughout the lifetime (but the bathtub curve shows a variation in this rate).

An important consideration is that the composition of both parts of the end-of-life flow differ because of the technology evolution throughout history. At the initial years of this industry, the induction generator (specially the GB-DFIG type) was the clear dominant, with more than 60% of market share in the EU [29][159]. Its prevalence continued but diminished in the following years, as other types such as DD-EESG for onshore wind turbines, and GB-SCIG and GB-PMSG in offshore installations, became increasingly relevant. Specially the electrically excited generator was the most used direct drive type for large wind turbines in 2016 [160]. From a material point of view, gearbox and direct-drive types mainly differ in the concentration of aluminum (Al), copper (Cu) and rare-earth elements (REE). Thus, for example, the flow of failed components contains a certain amount of permanent magnet synchronous generators, with critical materials such as Nd and Pr. However, these are not present in decommissioned wind turbines because in 1996 there was no significant installation of PMSG. This will be further discussed in section 5.2.

From the share of decommissioned material, 50.4% correspond to the tower, 31.4% to the nacelle and 18.3% to the rotor (blades). The tower contains a considerable share of the material and its collection and treatment is appropriately managed to reach circularity. Current investigation is focused on improving the end-of-life management of blades and nacelle, which also contain most of the critical materials [161].

Another relevant insight from Figure 22 is that, in the case of wind turbine technology, the research on component failure is crucial to perform an accurate evaluation of the amount of material that will be needed in repairing and replacement tasks, and therefore needed during the WT cycle. This matter is widely studied because of the effect it has in the levelized cost of energy[4] due to the influence of failure in the system performance and power output [162][129]. In addition, the breakdown and maintenance costs are significant parts of the WT's operation and maintenance expenditure. Even though its importance, consistent failure rates are not straightforward to find in the literature. Dao et al. [162] state that large variations in both failure rates and downtimes (time when WT is not technically available) are observed on data from around 18 thousand WT. In addition, studies about this issue also follow different approaches and reliability metrics, making results comparison even more difficult [9]. Examining the data from Shammugam et al. [117] (used in this thesis), the component with highest failure rates, involving a minor repair in most of the cases, is the pitch. It accounts for around 21% of all failures in WT and for 23% of all downtime, as reported by Vanni et al. [163]. They also argument that pitch systems are mounted in the rotating hub of turbines and they are often exposed to extreme ambient conditions; including high temperature, humidity and vibration. In addition, they are held stationary for long periods of time. The major sources of failure are hydraulic fluid leaks, bad lubrication of the rotary joints and bearings' overload [163][164]. The focus on upgrading the pitch is increasing, specially in improving the pitch bearing grease and balancing the load on the contact area.

Concerning the generators, the one with highest failure and that implies a highest material requirement is DFIG. Efforts are being made to improve its performance [165]. Conversely, PMSG are the generators with lowest failure rates mainly because they can be used without a gearbox [68]. Lastly, the component that implies the highest amount of material for repairing is the gearbox, due to its high rate of major replacement and its material intensity. Usual damage mechanisms include micropitting[5], scuffing, fretting corrosion and false brinelling[6], among others [166]. This problem is even worse in the case of offshore wind turbines due to the high variable wind loads that they experience [167].

Moving forward on the MSA discussion, at the end-of-life treatment it is estimated that 94% of the material goes to functional recycling, 2% to non-functional recycling, while the rest is directly disposed (nominal values shown in the right part of Figure 22). More than 30% of the material going to disposal is categorized as "others", which mainly corresponds to the polymers and polymer composites from the nacelle and the blades. The cover from the nacelle is dismantled and separated from the metals and electronic parts. It also contains epoxy and polyester resin. This composition allows designers to meet size, complex geometric and

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[4] The Levelized Cost of Energy calculates the value of the total cost of building and operating a power plant (in this case a wind farm) over an assumed lifetime and divided by energy production. It allows the comparison of different technologies [201].

[5] Micropitting is a Surface-initiated fatigue phenomenon occurring between interacting surfaces in which a cluster of micropits presents a grey-coloured appearance [202].

[6] False brinelling is a type of fretting wear which occurs in the roller bearings due to linear or rotational vibrations [203].

weight requirements of the cover [168]. A certain amount of composite also corresponds to the fiberglass in decommissioned blades (coming from the EoL rotor), which are cut or shredded to make landfilling feasible and comply with density protocols [150][117].

The highest recycling rates are achieved for the steel-related components, being almost 94% of the recycled flow. The remaining corresponds to copper, aluminum and a modest share of precious metals. The high recycling potential of steel is an advantage for the circularity of wind turbines because of the elevated concentration of this material. Steel scrap is regarded as a valuable raw material and it has a well-established market [169]. Its main drawback is that it is produced in a large number of different alloy compositions, with various alloying elements such as chromium, manganese, nickel or boron, which increase the complexity of steel recycling. The elements that cannot be removed by steel smelting processes are called tramp elements and they are of major concern for future steel production [170].

In the case of aluminium, recycling is increasingly boosted from an environmental point of view because it generates much less impact than primary production and saving almost 95% of energy requirement [171]. It can be recycled repeatedly without significant loss of properties but some impurities could be accumulated [172]. Similarly, copper is fully recyclable with almost no loss of quality and it implies great energy savings when compared with primary processing. However, some problems can occur due to elements integrated in the components along with Cu such as Al [121].

In literature an important research effort is targeted towards improving blade and generators' recycling. The former is of great interest [173] and their fully recycling remains a challenge due to the complex structure of layers united in one piece, as well as the recycling of the composite material itself [174]. The use of high-performance thermoset polymers as the matrix of these composites makes their recovery extremely difficult. Current recycling methods include mechanical recycling, high voltage fragmentation and thermochemical treatment by solvolysis. However, new technologies are needed to recover this material in an efficient and economical way [175].

Going back to Figure 20, the next aspect to analyse is the trade of secondary material. As a great share of this recycled flow corresponds to steel-related components, the trade of material is just analysed in the case of steel. A total amount of 83 kt were exported in 2016.

Finally, the material that ends up re-entering the cycle are 394 kt (G.1.2), which is a 19% of the raw material needed at the beginning of the value chain. Note that the material that arrives at recycling in 2016 will be useful as raw material in the following year. Reflecting on the future evolution of this amount after 2016, from one side the material obtained from decommissioning wind turbines may broaden because of the positive increase in the newly installed capacity after 1996. However, on the other side, the material requirements for new installations are as well escalating with the progress of wind energy. Efforts are required to improving material efficiency by implementing alternative turbine designs, efficient production techniques [176], material substitutions [177] and highly reliable components [178].

5.2. “Parent” layer

Figure 23 presents the flows and stocks of the “parent” layer of the analysis. In this case, the flows presented in the previous section have been divided in the two types of drivetrain systems: gearbox (GB, in orange) and direct drive (DD, in green).

The first clear result is that the gearbox technology dominates over the direct drive one. The share of gearbox over the total flow for each main parameter of the analysis is presented in Table 4. The mass percentages were calculated with the results from Figure 23.

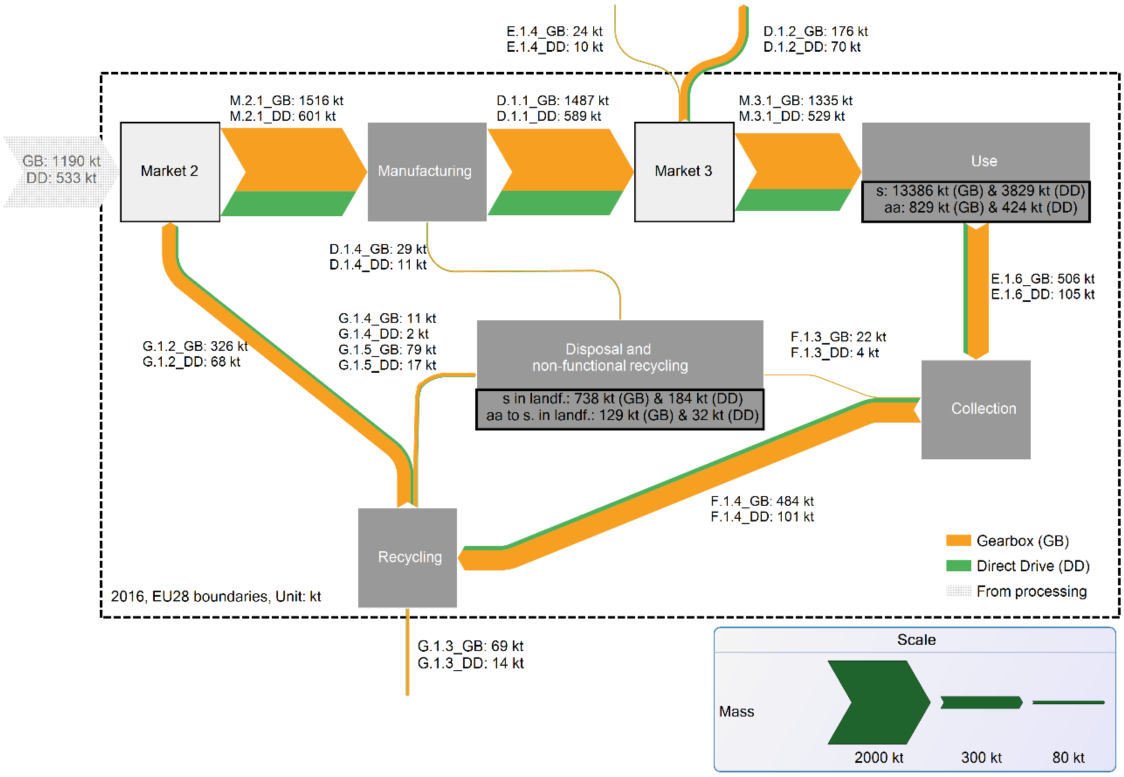

Figure *23* Flows and stocks of the whole wind turbine material cycle divided in the two main types of drive train systems: gearbox (GB, in orange) and direct drive (DD, in green). The dotted flow represents the material coming from the previous part of the life cycle (from processing). The abbreviations “s” and “aa” correspond to stock and annual addition to stock, respectively. Note that in the case of end-of-life (central box) the stock and annual addition refer to the ones in landfill (without considering non-functional recycling).
Differences of 1 kt can be encountered due to approximations.

Table 4 Share of material that corresponds to gearbox technology in each of the main flows of the "parent" layer.

Flow	GB / (GB + DD)
M.2.1 & D.1.1 & M.3.1	71.6%
E.1.6	82.8%
F.1.4 & G.1.2	82.7%
In-use stock (E.1.1)	77.8%
Stock in landfill (F.1.5)	80.1%

In the case of the initial flows M.2.1, D.1.1 and M.3.1, the gearbox type represents almost 72% (as presented in Table 4) of the total flow. This is the lowest share compared to the rest of the flows and could continue decreasing because of the tendency in installing more direct drive generators. Indeed, the newly installed wind turbines in the EU with DD has grown from 17% in 2006 until 32% in 2016 [29]. This technology was introduced to eliminate gearbox failure and transmission losses. Even though each type of drive train has its technical advantages that make them suitable in specific niche markets, some experts indicate that DD will ultimately become the dominant technology [36]. The reason is three-fold:

1. The costs of offshore structure for DD are lower than for GB due to overall lower weight.
2. DD has more potential for future improvement. It is predicted that GB is reaching its maximum efficiency point, while DD still has more room for development.
3. In the future, higher power ratings will be pursued for WT installations and DD is expected to be more efficient in reaching them. The obstacle in GB designs is that they require extra stages of gears for upgrading the power output, which leads to more energy losses.

The values of gearbox contribution shown in Table 4 indicate that after the use phase, the GB share is a bit higher, around 83. This is due to the fact that most of the decommissioned wind turbines that were installed in 1996 contained gearbox drive trains. In addition, among the failed components (which are also part of the parameter E.1.6), the generator with highest failure and highest material consumption is the GB-DFIG.

Comparing the final flow G.1.2 and the initial M.2.1, it was obtained that in the case of gearbox drive trains the circularity is 22% (so 22% of the initial material can be obtained through recycling) whereas in the case of direct drive is just 11%. For the moment, this result might not imply any issue for the wind energy industry because in 2016 the most usual newly installed capacity was still GB-DFIG. Therefore, if the material that re-enters the loop corresponds to the same type of wind turbine, it can be more easily reused for new installations. However, as it was previously mentioned, the increase in power output, dimensions and efficiency of future wind turbines might lead to a tendency towards direct drive technology, which will require additional materials than the ones obtained from closing the loop (because the recycled ones will mainly correspond to gearbox systems).

Reflecting on the material composition of these flows, as this layer focused on the distinction between drive train systems, there are some materials present in other wind turbine components, mainly tower and blades, that are found in the same concentration in both DD and GB turbines. This is the case for example of zinc, polymers, glass and carbon composites. Slight differences in composition are present for cast iron, chromium and manganese [16].

The materials with greater differences between both configurations are aluminium, that is present twice more concentrated in GB than in DD, and copper, whose concentration is 3.5 times higher in DD than in GB. The variation is also considerable in the case of rare earth elements (REE) such as neodymium, praseodymium and dysprosium. In the DD case their concentration is higher, especially with PMSG. In GB drive trains, there are some wind turbines that also contain permanent magnets (in a combined configuration). In addition, it is also usual that they contain a slight amount of PM in the tower, to securely attach ladders and other equipment [16][179]. The exact values of the material concentrations for each drive train type are present in Annex 8.4 (Table 13).

5.3. "Child" and raw materials layers

This section presents the results and discussion for the three last layers described in Figure *17* of the methodology. A general assessment of the "child" layers is developed at the beginning, diving into Ni, Mn and Nd cycles individually in the following subsections (5.3.2, 5.3.3, 5.3.4), as well as comparing their presence in WT with the rest of market applications (5.3.5). A final note on the future trends in the demand, supply and recycling of these raw materials is also included.

5.3.1. General analysis of "child" layers

The "child" layers of the multilayer assessment are presented in Figure *24*. The three colors represent each of the selected materials of this analysis: nickel (green), manganese (pink) and neodymium (blue). In addition, the whole MSA is divided in two concentric cycles: the external one for the Ni, Mn and Nd embedded in GB drive trains and the inner cycle corresponding to DD. All values are presented in metric tons (t). Note that in certain flows (D.1.4, E.1.4, D.1.2, F.1.3, G.1.4 and G.1.5) the values of GB and DD were summed up for each element to enhance visualization. This can be identified in Figure *24*, where the corresponding label does not specify whether it corresponds to GB or DD, indicating that they were aggregated.

Both types of drive trains contain a similar concentration of manganese, with differences of around 10 t/GW, mainly situated in the tower, in gearbox and in several nacelle parts [65]. The amount of nickel differs a bit more, with a variation of between 100 and 200 t/GW, depending on the type of technology, due to its presence in gearbox and generators. For neodymium the differences are even higher because it is directly related to the presence of permanent magnet in the different types of generators.

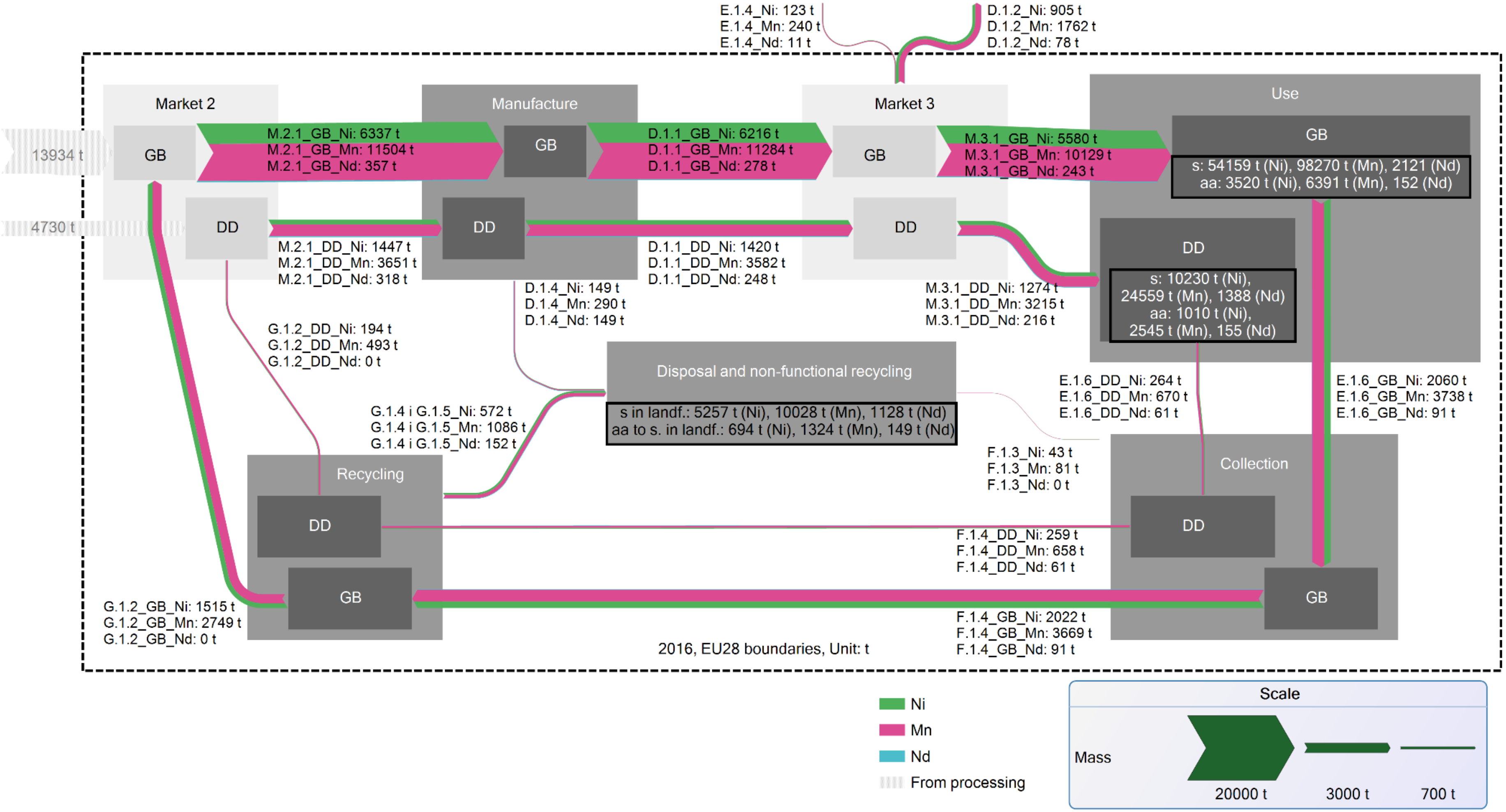

Figure 24 Flows and stocks of nickel (green), manganese (purple) and neodymium (blue) in the wind turbine cycle. The dotted flows represent the material coming from the previous part of the life cycle (from processing). This diagram also presents the division in gearbox (GB) and direct drive (DD) drive train types. Differences of 1 kt can be encountered due to approximations.

In general, it can be noted from Figure *24* that the demand of manganese is higher than the one of Ni (almost twice the amount), and both of them are much predominant than Nd. The initial amount of each material needed in wind turbine manufacturing in the EU (M.2.1), summing up GB and DD requirements, is around 7800 t of Ni, 15155 t of Mn and 700 t of Nd. Even though Nd is the rare-earth element in highest concentration within permanent magnets, its overall presence in wind turbines is relatively low as compared to Ni and Mn (accounting for only 5% of the total Mn amount). To enhance clarity and facilitate visual understanding, Nd's material flows are presented separately in a dedicated figure (section 5.3.4).

5.3.2. Nickel case

Nickel is an essential material in the production of stainless steel. In onshore wind power it is used mainly in the gearing and generator components. In offshore, given the corrosive marine environment, there are many more opportunities for stainless steels and for Ni [180].

Diving into the different kinds of material, the Austempered Ductile Iron (ADI) is a cast iron in which carbon is present as graphite nodules in a matrix of ferrite and austenite. It has high strength and ductility, and the presence of nickel, molybdenum and copper promotes hardenability. It has twice the tensile and yield strength of standard ductile irons. ADI contains between 0.6 and 2.5 wt.% of Ni and it is present in the gearbox, the main frame (which supports the entire turbine drive train), the main shaft (which transfers the rotational force of the rotor to the gearbox) and the rotor hub. In most of the cases it is combined with other alloys such as low alloys, CrMo steel or spheroidal cast iron [61]. They are praised as having 100% of recyclability [181], but no evidence has been found on whether this is the case for WT.

Another crucial alloy containing Ni is the heat-treatable carburizing steel 18CrNiMo7-6, which is the standard gear steel for windmill gearboxes and it is also present in the screws and studs. It contains between 1.4 and 1.7 wt.% of Ni and it provides deep hardening ability and strong resistance to fatigue [61].

As the standard material for gearbox production contains relevant concentrations of Ni (higher than in other WT components), this explains why the concentration of nickel in GB wind turbines is higher than in DD.

Concerning the end-of-life, Nakamura et al. have studied the recyclability of this kind of alloys and the potential recovery of alloying elements (Cr, Mn, Mo and Ni). They praise that 80% of postconsumer Ni in the whole economy is recovered within the Ni cycle and that the remaining 20% is lost in carbon and copper scrap [100]. The latter is unrecoverable for uses that take advantage of nickel's properties [59]. For the specific case of wind turbines, the share of recyclability is determined as a bit higher, in line with the steel end of life, with around 2%

ending up in disposal with landfilling and 3% in non-functional recycling (C and Cu scrap). The rest is estimated as functionally recycled [150].

Overall, in 2016 a 21.9% of Ni that was needed for manufacturing could be recovered and kept in the cycle with recycling, which is a greater value than in the case for the whole wind turbines but still low in order to reach circularity (far from the ideal 100%).

Reck et al. analysed the anthropogenic nickel cycle and state that nickel stocks are growing and that the long lifetimes of its products (such as WT) mean that currently there are limited opportunities to replace primary sources by postconsumer scrap. The performance should improve in primary mining and smelting stages. However, the efficiency of end-of-life recovery should be maximized, thus eventually it should become an integral part of product design [59].

5.3.3. Manganese case

In the manganese cycle, a higher amount of material is involved in comparison with Ni and Nd. Therefore, the in-use stock is also the highest (around 123000 t) and the stock that ends up in landfill is ten times lower than the in-use case, around 10000 t.

Apart from iron, manganese is one of the most essential minerals in the production of steel, reason why it is classified as a ferrous metal [64]. In wind turbines, according to a report from ArcelorMittal, Mn is present in the tower, in gearbox and in several nacelle parts [65].

In the case of towers, around 85% are built with quarto plate, which is a hot-rolled plate with standard structural steel grades S235, S275 and S355 [65], with maximum levels of 1.6% of Mn [182]. Moreover, gearbox components are made of seamless rolled ring steels, such as 34CrNiMo6 or 18CrNiMo7-6, which contain 0.5-0.9 wt.% of Mn [66]. In the case of the nacelle, apart from quarto plates, low alloyed forged rings are also utilized.

Finally, small amounts of manganese may be added to bronzes and brasses along with copper to improve machinability, corrosion resistance or other properties [64].

In all these cases, the steel-related material can be functionally recycled with a high yield and just around 5% of the material is considered lost or non-functionally recycled [150]. However, disagreements are found in the literature and these assumptions might imply an error. For instance, Hagelstein et al. reported that the old scrap collection rate for manganese of iron and steel is 37%, with an end-of-life recycling rate estimated as 53% [183] [184].

At the end of life, manganese that is functionally recycled and re-enters the cycle (G.1.2 of Figure 24) is around 21.4% of the initial flow (M.2.1), a considerable amount but with room for improvement.

5.3.4. Neodymium case

The case of neodymium is especially insightful to analyse because of its predominant role as part of permanent magnets. Figure *25* presents the MSA of Nd for the wind turbine cycle in the EU28 in 2016. In this Sankey diagram each arrow is divided in two colors corresponding to GB (orange) and DD (green) systems (same color code as in section 5.2).

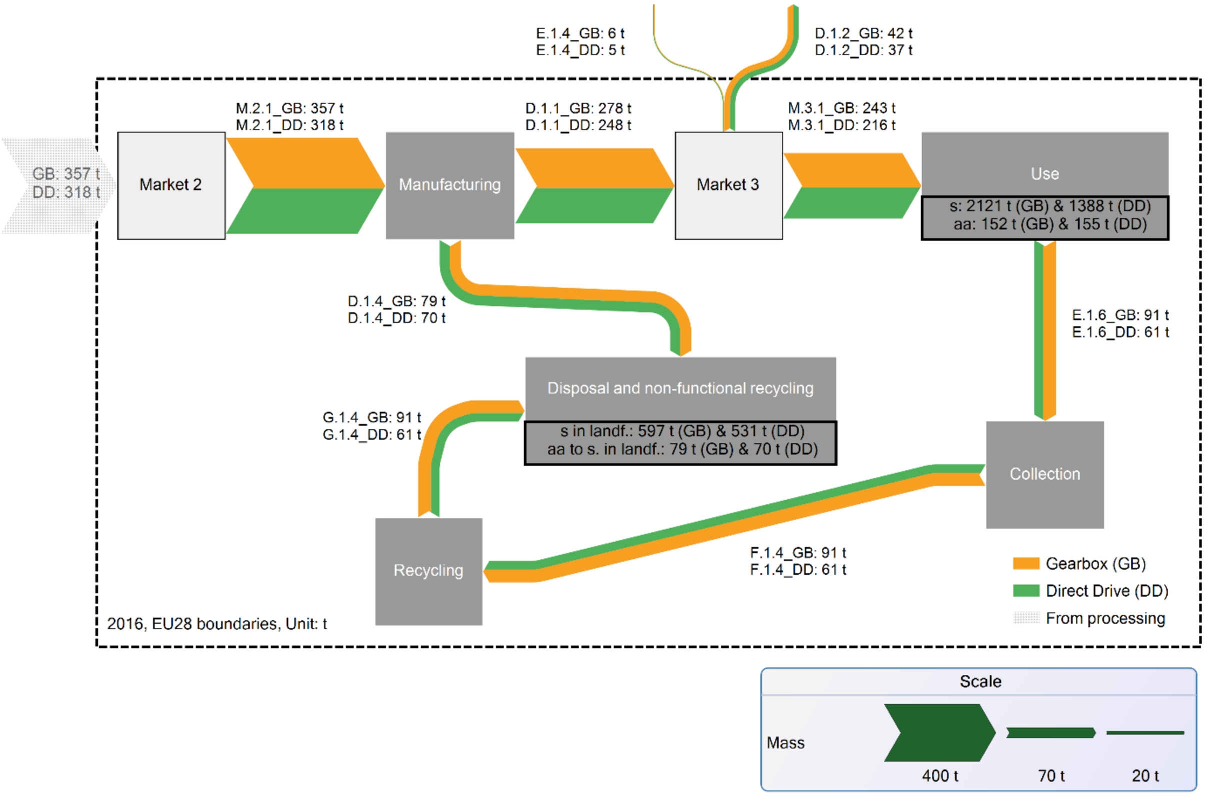

Figure 25 Flows and stocks of neodymium in the wind turbine cycle in the EU28 in 2016. The two colours differentiate the material in gearbox (orange, GB) and in direct drive (green, DD).
Differences of 1 kt can be encountered due to approximations.

One major difference in this case with respect to the Ni and Mn MSA is that the amount of Nd in 2016 embedded in GB systems is really similar to that of DD and approximately 50% of each flow correspond to each kind of technology. This is due to the fact that, even though there are more newly and cumulative installed GB wind turbines than DD, the concentration of Nd in DD technologies is much higher. Indeed, several studies have reported the concentration of permanent magnets, and thus of Nd, in different generator types [117][185]. Viebahn et al. estimated that the specific weight of PM in DD is around 650 kg/MW and for GB between 0 and 160 kg/MW [185]. These magnets contain 31% of Nd, whose value coincides with the ones reported by the JRC and that were used in the present analysis [29]. The number of magnets must be higher in the case of direct drive technologies because, without gears, the appropriate frequency of the generated electricity has to be reached through a PM system. Regarding the manufacturing waste (D.1.4), according to Horikawa et al., around 15-30% of the raw materials in NdFeB magnets are wasted as scraps in manufacturing sites during shaping and finishing [186]. This fact is considered in the present MSA, so the flow D.1.4 is considerable in comparison with the total Nd needed for manufacturing (M.2.1).

At the end of life, neodymium is mainly non-functionally recycled. The EoL magnets in WT have a high collectability. Then, they are preprocessed with effectiveness since magnets are large, can be identified with ease and separated adequately [51].

Even though all the preprocessing is possible, at the recovery stage neodymium is lost or dissipated through non-functional recycling within other materials cycle [67]. According to a review by Yang et al. (2017), no real recycling of NdFeB wastes takes place, at least not in Europe until 2017 [70]. Some authors consider that magnet scraps are exported to China and Japan for metallurgical recycling [187], but no specific amounts were found in the literature, so all Nd from wind turbines at end-of-life is considered ending up in non-functional recycling (G.1.4). The Center for European Policy Studies reported that PM recycling is not yet currently developed at scale in the EU because of a combination of regulatory, financial, supply chain and technological constraints [153].

The EU recycling of magnets is currently under development and several approaches are being studied for reuse, reprocessing and recovery. One possibility is direct reuse, which should be theoretically possible but in practice is complicated due to the fast development of magnet-containing technologies as well as the difficulties in extracting them with no damage and cleaning them without compromising the dimensions [70].

Reprocessing of the alloy would be ideal to utilize again the material in the production chain of PM. However, it is complicated to trace and prevent the presence of impurities, which cause deterioration in the magnetic properties (even at really low concentration, at ppm range). If the composition of magnetic scraps is known and homogeneous and impurities are removed, this could be an opportunity to consolidate the EU production of high-end magnets [187].

Finally, the recovery of raw materials would allow their utilization in other applications. Some studies state that magnets are generally treated by hydrogen decrepitation, which has a high recovery efficiency, no production of toxic process chemicals, low GHG emissions and no interference with recovery of other metals. However, it has intermediate maturity. Another option would be to apply hydrometallurgical and pyrometallurgical technologies, which are more mature and have similar recovery rate but with higher environmental impacts [51]. Despite disadvantages such as high consumption of chemicals and the production of wastewater, hydrometallurgical processes are considered the most promising [187].

March et al. [188] conducted an LCA comparing these three recycling options and concluded that they all show clear environmental advantages in comparison with the primary production of neodymium. Therefore, when these challenges are overcome, the flow of non-functional recycling (G.1.4) will diminish in favor of an increase in the functionally recycled Nd (G.1.2), and therefore an increase of the circularity of the material.

5.3.5. Comparison with the rest of applications and future evolution of the demand of selected raw materials

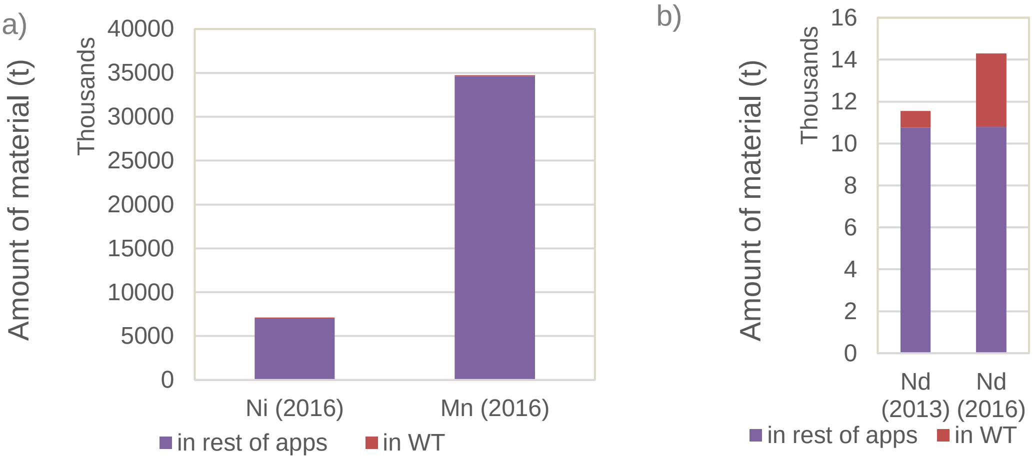

Figure 26 Amount of Ni, Mn (a) and Nd (b) present as in-use stock in the EU28 in 2016 and, in the case of Nd, as well in 2013. The purple bar indicates the total amount in all the applications of the market and in red the amount just in wind turbines (WT).

In this final section, the studied materials present in wind turbines are compared to their role in all market applications. Figure *26*a shows the in-use stock in the EU28 in 2016 of Ni and Mn and Figure *26*b for Nd in 2013 and 2016. The amount in all applications is presented in purple and the one embedded in WT in red. For the cases of Ni and Mn (Figure *26*a), the share in wind turbines is really low (0.9% and 0.35% respectively) compared to the rest of applications, due to the high utilization of these materials in other industry sectors. Ni main end-use sectors are engineering, metal goods and transport [57]; and for Mn are construction, machinery and transportation [189]. In the case of Nd (Figure *26*b), the share is much higher and it corresponds to almost 25% of the quantity necessary in all applications in 2016.

The same calculations were performed with data from 2013. In the case of Nd the results are presented in Figure *26*b and in the cases of Ni and Mn the values are shown in Table *5* (it was decided like this to optimize the results visualization). It can be observed that in all three cases the percentage of material present in wind turbines showed an increase in 2016 compared to 2013. This escalation was especially significant in the case of neodymium, in which the in-use amount multiplied more than 3 times.

Table 5 Amount of Ni and Mn present in wind turbines and in the rest of applications (in kt) in 2013 and 2016. In the last row, the share of material present in WT with respect to all applications is showed.

	Ni (kt)		**Mn (kt)**	
	2013	**2016**	**2013**	**2016**
in WT	49	64	93	123
in rest of apps	7135	7070	34750	34627
share in WT	0.68%	0.91%	0.27%	0.35%

This result provides an insight on which might be the future evolution of this analysis. The wind turbine sector continued developing after 2016 and was expected to boost in the following years. The JRC estimates that the EU wind capacity will reach 300-500 GW in 2030 and that the material demand will increase around 1.5 times (with respect to the one in 2020) [8]. It also reports that, among the strategic materials, nickel shows the highest demand, reaching numbers between 6 and 12 kt in 2030.

Finally, the use of Nd followed an increasing trend along the studied years and continued to increase afterwards. The JRC estimates that almost all offshore wind turbines and 13% of onshore newly installed in the EU in 2020 used permanent magnets [8], which means an increase of Nd's demand in a 17% with respect to 2016. It is forecasted that its demand will reach between 760 t and 2300 t for WT (low and high demand scenarios) in 2030 [8].

This high demand implies a series of challenges for the EU industry. First, materials' supply should be secured through a diversified network and strong international partnerships. The dependency on China's processing should be diminished by sourcing from reserves in Australia, Malaysia, Canada, etc. In addition, this should be followed by an increase of domestic supply (improving EU's mining and refining opportunities) and a robust implementation of recycling technologies. For instance, currently, the only operating magnet recycler in the EU is Kolektor collaborating with Magneti Ljubljana (both in Slovenia) [190].

Another future pathway would be material substitution. According to McKinsey [87], traditional steel will be substituted by high-strength steel (HSS, which contains a considerable amount of manganese). However, IRENA reports that no major changes in this regard will take place due to the high cost of HSS [191]. Aluminium and carbon fiber will also be increasingly used, as reported by both McKinsey and IRENA [87] [191].

In the case of REE, there is currently no competitive alternative solution to high-performance NdFeB magnets, so substitution in this regard might take place just as a long-term option. The focus in this decade is on being able to recover and reuse the materials embedded in PM, closing the loop of the value chain [8].

5.4. Uncertainty analysis, limitations and additional comments

In this work, different possible sources of uncertainty were identified. First of all, the calculation of the amount of material towards the manufacturing phase (M.2.1) was calculated through two different methods (explained in the methodology), and the results show a difference of around 43%. The result of equation (*7*) is 2117 kt (using the mass balance) and of equation (*8*) is 3024 kt. This second value was obtained from the number of “generating sets, wind-powered” reported by Eurostat [81]. However, it is unclear which are exactly the types of components contained in this PRCCODE and it is uncertain whether other generators producing energy from wind, but which are different from wind turbines, are also included in these statistics. This might be a reason why the value in the second case is higher than with the first method. Therefore, the result from equation (*8*) was considered less reliable and the other one was taken as part of the final MSA, as shown in Figure 20.

In the case of annual addition to in-use wind turbines (E.1.7), two calculation methods were also considered. The result obtained from the mass balance, 1252 kt, is almost 26% lower than the one obtained with equation (*13*) (reported in BIO by Deloitte), 1693 kt. This difference is coming from the fact that equation (13) assumes a certain performance in the increase of installed wind turbines (given a certain AG), that might not be completely fulfilled in reality. The evolution of the annual growth rate is shown in Annex 8.3, Figure *27*. To be consistent in the calculations, the result from the mass balance is the one employed in the final diagram.

For the rest of flows, the calculations were directly done with data obtained from the literature and that could not be cross-checked with professionals in the sector. Relevant uncertainty is present in the failure rates of the different components. The database used in this work ([117]) is an adaptation of data from wind farms around the European territory, mainly Germany, and from 2001 onwards. This data might differ from the failure rates of wind turbines of the whole EU28 since 1996, which is the target of this project. In addition, the amount of material that is required for minor and major repairs is obtained from own assumptions of Shammugam et al. [117]. Therefore, it might imply some error because the share of material replaced probably varies between components, however a fixed share is assumed for all components. Moreover, as already stated in the methodology section, failure rates are really variable and prone to change considerably with the surrounding factors, which might incur errors as well.

At the end-of-life phase, a realistic scenario is considered for material recycling. Nonetheless, the recycling rates might vary among countries, and certain studies incorporate both optimistic and conservative scenarios to obtain a range of results instead of a single value [42]. This approach would ensure a more comprehensive and nuanced understanding of the potential outcomes.

Furthermore, some limitations were encountered due to a lack of data. For example, in the case of metal recycling many information was found in the literature about techniques to treat lithium-ion batteries [192] but very few were found on how metals are recovered from the steel alloys in wind turbines.

Lastly, foundations were not included in the multilayer MSA but a final note on their circularity should be made for their relevance in the wind turbine sector. WindEurope reported in 2020 that the legislation for the foundations' decommission widely varies from country to country [120]. In some of them, they are partially removed or reused in upcoming projects, while in others they need to be completely removed. Li et al. assume in their end-of-life scenarios that bulk materials used in foundations are left in situ and their recycling is not considered [42]. Nevertheless, concrete, which represents 95.5% of onshore foundations and 5% of offshore foundations [117], can be recovered and recycled into aggregate for building materials, repurposed as a filling material or utilized for road construction. It is basically crashed to produce a granular product of a given particle size while magnetic separators remove remaining ferrous matter, mainly steel reinforced-bars [193]. Badraddin et al. state that the main challenges of concrete recycling are increased project duration, leading to material claim delays; lack of national programs and regulations specific on concrete recycling, and the currently low demand for recycled concrete, although it is gradually rising [194].

6. CONCLUSIONS

6.1. Main conclusions

This master thesis unveils the flows and stocks of materials in the wind turbine life cycle in the EU28, specifically focusing on the year 2016. Policy recommendations and energy reports demonstrate the escalating growth of the EU's installed wind turbine capacity in recent years, which justifies the imperative for a proper management of natural resources associated with this technology [8].

From a methodology point of view, a multilayer Material System Analysis was applied to achieve this thesis' goals, i.e. to analyse the EU's supply chain flows and stocks of materials in the WT industry. Previously, it was just implemented for Li-ion batteries, bringing some insights on the required policy needs [109]. Therefore, this methodology should be extended to the rest of strategic technologies in the EU economy, being WT at the top of this list. The multilayer MSA shows full potential to reveal the dependencies of WT material requirements with EU's capabilities. In the long term, the same study should be repeated with improved and more updated knowledge, so this thesis can be utilized as the reference for these future investigations in terms of calculations, data sources, assumptions, system boundaries and data analysis. A further discussion about prospective recommendations for future research is presented in subsection 6.2.

The "grandparent" layer (general for the whole wind turbine) showed that 2117 kt of material were needed as input to the manufacturing phase. Trade of materials in the analysed phases were low, so the EU28 in 2016 was a world leader in wind turbine components and assemblies' manufacturing. In addition, due to the high recyclability of steel and iron, 94% of material at end-of-life was functionally recycled.

A relevant outcome of this work was the focus on the material needed to repair or replace failing wind turbine components. This was a significant share (77%) of material that arrived at the end-of-life, with a notable contribution from failed gearboxes. However, considerable uncertainty was found in the literature for failure rates of wind turbine components and a more refined analysis of this concept should be done in the future.

Concerning the functional recycling of materials, steel-related components exhibit considerable potential, offering a key advantage to achieve circularity in the wind turbine cycle. Similarly, aluminium and copper also present favourable characteristics, as their recycling consumes less energy compared to primary processing. At the collection phase, global research efforts are targeted towards improving blade and generators' recycling.

It should be noted that 19% of the raw material needed at the manufacturing phase could be obtained from functional recycling. This value is really prone to change over the years because newly installed wind capacity follows an increasing trend (therefore, more raw materials will be needed at the beginning of the cycle) but more materials will be functionally recycled because as of 2016 more wind turbines arrive at end-of-life and are decommissioned.

Concerning the “parent” layer, the main conclusion is that most of the material flows (between 70-85%) correspond to GB. However, some authors state that DD technology will ultimately be the dominant [36]. Tracking the evolution of each type of technology is crucial in terms of material requirements. Regarding for example Al, Cu and REE, the differences in concentration are high and should be considered in material management decisions.

Finally, the analysis of Ni, Mn and Nd was assessed through the child and raw materials layers. The demand of Mn for the wind turbine manufacturing (15200 t) was almost twice the one of Ni (7800 t), and both of them were much more predominant than Nd (700 t).

In the case of nickel, its presence is strongly linked to that of stainless teel, being present mainly in the gearing and generator components, in materials such as austempered ductile iron and heat-treatable carburizing steel [61].

Concerning manganese, it is mainly present in the tower, gearbox and nacelle parts, as an essential component of steel. The typically utilized materials are quarto plate steel and seamless rolled ring steels [65]. Both Ni and Mn had a high recycling rate as part of steel-related materials. Their presence in wind turbines was still really modest (less than 1%) in 2016 compared to their usage in other sectors such as construction and transportation. However, the increase of material demand for wind turbines combined with Ni and Mn recent classification as CRM [52] implies a necessary tracking of their usage in the coming future.

In the case of Nd, the life cycle presented a contrasting picture if compared to Ni and Mn. Even though its concentration was much lower, the associated criticality was exponentially higher. On one hand, Nd is an essential element in permanents magnets for the generator, with no feasible substitute so far and with no consolidated EU magnets recycling to recover it. On the other hand, Nd is also classified as a CRM [52], with serious challenges in its supply chain due to the reliance on China for extraction and metal refinement, alloying and magnet manufacturing [8]. This creates an undesired dependence of the EU on external countries. When comparing Nd’s presence in wind turbines with the rest of applications, 25% of the total Nd as in-use stock was embedded in wind turbines in 2016. If the forecasts about the future increase in DD-PMSG generator types are fulfilled, the supply of Nd might be threatened.

In general, due to the long lifetime of wind turbines, the dismantling, recovery and recycling of their raw materials was still in a premature stage in 2016 and there were limited opportunities to replace primary resources by postconsumer scrap. However, flows and stocks of materials in the wind turbine life cycle have increased and will continue to do so exponentially. Therefore, solutions for the management of its materials and a strong EU’s supply chain should be of priority to ensure a smooth green transition.

6.2. Recommendations for future research

The primary recommendation for this work is to update the multilayer MSAs with more temporally recent data. Due to the limited access to information, the chosen year of analysis was 2016, which was 7 years prior to the submission of this thesis. During this period, from 2016 until 2023, both the wind energy sector and the overall economy in the EU dramatically changed: the installed wind capacity increased in 90 GW [195], policy-driven advancements were set towards the procurement of greater amounts of green energy [196], a global pandemic created disruptions in almost all sectors [197], to name a few transformative events. In addition, the amount of decommissioned wind turbines increased since 2016 because more equipment arrives at end-of-life. Consequently, the sector is gaining more experience in dismantling and managing these resources, which could be reflected on the MSA and the insights it can yield. In this regard, special attention should be given to wind turbine repowering projects, which might extend the lifespan equipment with minimal material usage.

From a material point of view, this study should be completed in the future with the specific analysis of other CRM present in WT as part of the “child” layer, such as aluminium, dysprosium and praseodymium.

Concerning data availability, more transparency is required in the future on the products included in the codes provided by PRODCOM, the EU’s statistics service. For the case of wind turbines, it is not clear which components are included in the reported goods. This leads to a limitation in the knowledge on the raw materials necessary in the EU for WT manufacturing and for trading. Higher accuracy is also necessary for the estimation of failure rates of the wind turbine parts, as well as their material consumption when repaired.

Furthermore, international standards are required, for example, for the decommissioning of wind turbines [120], which do not exist yet. Policymakers should focus as well on the diversification of materials supply, enhancing domestic mining, boosting the circularity of the value chain and building up substitution solutions [8].

The future of wind turbine technology is promising and might bring some innovations that completely change the presented trends of material flows and stocks in the EU. Manufacturers are developing next-generation technology [4], better floating offshore wind turbines [198], recyclable composite of the blades and lightening of their weight [17], disruptive types of equipment (for example with wood towers [199]) and advanced installation and service logistics [200]. Therefore, as future work, a reconsideration of the ”parent” layer might be convenient as well, dividing the technology by types of blades or by several generator features, to name a few possibilities.

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8. ANNEX

8.1. Failure rates of wind turbine components

Table 6 Failure rates of wind turbine components.

	WIND TURBINE COMPONENT							
				GENERATOR				
Type of failure:	Pitch	Yaw	Gearbox	DFIG	DD PMSG	GB PMSG	DD EESG	SCIG
Major replacement	0.001	0.001	0.051	0.109	0.009	0.008	0.109	0.109
Major repair	0.179	0.006	0.036	0.356	0.03	0.025	0.356	0.356
Minor repair	0.824	0.162	0.369	0.538	0.546	0.455	0.538	0.538

8.2. Model for mass component estimation

Table 7 Scaling factors (b) and constants (a) for the mass model of the failing components of a wind turbine.

	Pitch	Yaw	Gearbox	Generator				
				DFIG	PMSG - DD	PMSG - GB	EESG - DD	SCIG
log (a)	-4.3	-5.8	-2.5	-2.2	-1.3	-2.1	-1.2	-2.2
b	2.5	3.3	1.9	1.6	1.6	1.6	1.6	1.6

Table 8 Scaling factors (b) and constants (a) for the mass model of the various parts of a wind turbine.

	ROTOR	NACELLE					TOWER
		DFIG	PMSG - DD	PMSG - GB	EESG - DD	SCIG	
log (a)	-3.3	-2.3	-3.4	-2.3	-3.3	-1.2	-4.2
b	2.6	2.1	2.7	2.2	2.7	1.6	3.2

8.3. Market analysis: market shares, annual growth rate and installed capacity

Table 9 Market shares of each drive-train system, classified by newly installed (“New”) wind turbines and the in-use ones (cumulative, “Use”), as well as per year and per location of the wind turbines: onshore (“Ons.”) VS offshore (“Offs.”).

	2006				**2007**				**2008**			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
GB-SCIG	12.0%	0.0%	10.0%	0.0%	4.4%	48.9%	10.9%	10.9%	3.6%	0.0%	10.0%	7.0%
GB - WRIG	4.0%	0.0%	5.0%	0.0%	2.8%	0.0%	3.8%	0.0%	3.0%	0.0%	3.7%	0.0%
GB-DFIG	64.9%	100.0%	65.0%	100.0%	74.8%	44.4%	66.4%	87.6%	66.3%	95.4%	66.4%	90.4%
GB-PMSG	1.5%	0.0%	0.0%	0.0%	0.3%	6.7%	0.0%	1.5%	0.5%	4.6%	0.1%	2.6%
GB - EESG	0.4%	0.0%	0.4%	0.0%	0.4%	0.0%	0.4%	0.0%	0.7%	0.0%	0.4%	0.0%
DD-PMSG	0.2%	0.0%	0.2%	0.0%	0.2%	0.0%	0.2%	0.0%	0.6%	0.0%	0.3%	0.0%
DD-EESG	17.0%	0.0%	20.0%	0.0%	17.1%	0.0%	19.6%	0.0%	25.3%	0.0%	20.3%	0.0%

	2009				**2010**				**2011**			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
GB-SCIG	6.0%	26.1%	9.4%	12.7%	3.7%	13.3%	8.8%	12.9%	6.4%	5.4%	8.5%	11.3%
GB - WRIG	4.6%	0.0%	3.8%	0.0%	1.5%	0.0%	3.6%	0.0%	0.9%	0.0%	3.3%	0.0%
GB-DFIG	59.9%	66.1%	65.5%	83.1%	62.4%	86.7%	65.1%	84.3%	60.2%	94.6%	64.6%	86.5%
GB-PMSG	3.3%	7.5%	0.5%	4.1%	8.5%	0.0%	1.5%	2.8%	4.0%	0.0%	1.7%	2.2%
GB - EESG	0.3%	0.3%	0.4%	0.1%	0.1%	0.0%	0.4%	0.1%	0.5%	0.0%	0.4%	0.0%
DD-PMSG	0.5%	0.0%	0.3%	0.0%	0.1%	0.0%	0.3%	0.0%	1.5%	0.0%	0.4%	0.0%
DD-EESG	25.5%	0.0%	21.0%	0.0%	23.7%	0.0%	21.3%	0.0%	26.5%	0.0%	21.8%	0.0%

Table 10 (follows from previous page)

	2012				2013				2014			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
GB-SCIG	9.1%	0.0%	8.6%	8.5%	6.4%	78.4%	8.4%	25.7%	2.9%	59.4%	7.9%	32.0%
GB - WRIG	2.1%	0.0%	3.2%	0.0%	1.4%	0.0%	3.0%	0.0%	0.3%	0.0%	2.7%	0.0%
GB-DFIG	48.9%	100.0%	62.9%	89.8%	57.3%	13.6%	62.3%	71.0%	35.7%	16.3%	60.0%	60.9%
GB-PMSG	15.9%	0.0%	3.3%	1.7%	15.1%	6.5%	4.4%	2.8%	20.8%	12.3%	5.9%	4.6%
GB - EESG	0.6%	0.0%	0.4%	0.0%	0.1%	0.0%	0.4%	0.0%	0.0%	0.0%	0.3%	0.0%
DD-PMSG	1.5%	0.0%	0.5%	0.0%	5.0%	1.5%	0.9%	0.4%	8.7%	12.0%	1.6%	2.5%
DD-EESG	22.0%	0.0%	21.8%	0.0%	14.7%	0.0%	21.2%	0.0%	31.6%	0.0%	22.1%	0.0%

	2015			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**
GB-SCIG	0.7%	37.7%	7.4%	33.5%
GB - WRIG	0.1%	0.0%	2.6%	0.0%
GB-DFIG	45.9%	13.4%	59.0%	47.8%
GB-PMSG	22.8%	42.8%	7.1%	15.1%
GB - EESG	0.0%	0.0%	0.3%	0.0%
DD-PMSG	7.1%	6.2%	2.0%	3.5%
DD-EESG	23.4%	0.0%	22.2%	0.0%

	2016			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**
GB-SCIG	1.8%	48.5%	7.0%	35.4%
GB - WRIG	0.2%	0.0%	2.4%	0.0%
GB-DFIG	40.8%	14.9%	57.6%	43.7%
GB-PMSG	21.8%	27.6%	8.2%	16.7%
GB - EESG	0.0%	0.0%	0.3%	0.0%
DD-PMSG	7.9%	9.1%	2.5%	4.2%
DD-EESG	27.5%	0.0%	22.6%	0.0%

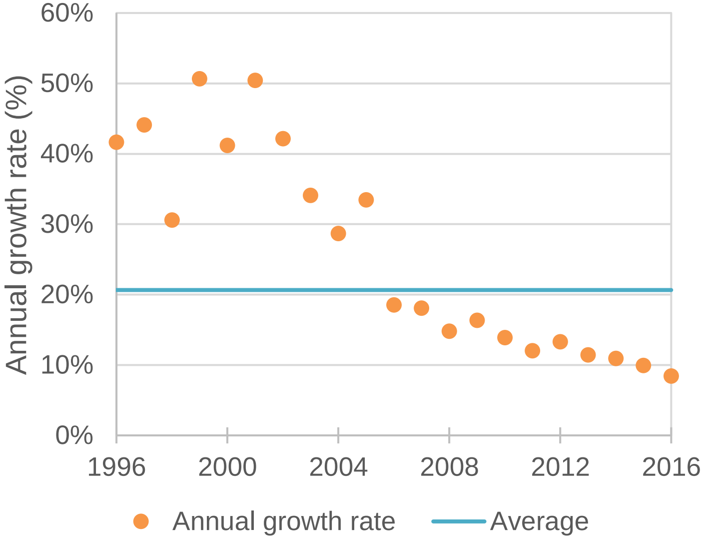

Figure 27 Annual growth rate of wind turbine installations.

Table 11 Market analysis with the newly installed (“New”) wind capacity and the in-use (cumulative, “Use”) capacity, classified per year and per location of the wind turbines: onshore (“Ons.”) VS offshore (“Offs.”).

	1996				**1997**				**1998**			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
Capacity (GW) of new or in-use	1	0	3.4	0	1.5	0	4.9	0	1.5	0	6.4	0
TOTAL (GW)	1		3.4		1.5		4.9		1.5		6.4	

	1999				**2000**				**2001**			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
Capacity (GW) of new or in-use	3.2	0.0	9.6		3.8	0.0	12.9	0.0	6.4	0.1	17.2	0.1
TOTAL (GW)	3.2		9.6		3.8		12.9		6.5		17.3	

	2002				**2003**				**2004**			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
Capacity (GW) of new or in-use	7.1	0.2	22.9	0.3	7.8	0.1	28.2	0.4	8.1	0.1	33.9	0.5
TOTAL (GW)	7.3		23.2		7.9		28.6		8.2		34.4	

	2005				**2006**				**2007**			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
Capacity (GW) of new or in-use	11.4	0.1	39.9	0.6	7.4	0.1	47.3	0.7	8.5	0.2	55.8	0.9
TOTAL (GW)	11.5		40.5		7.5		48.0		8.7		56.7	

Table 12 (follows from previous page)

	2008				2009				2010			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
Capacity (GW) of new or in-use	7.9	0.5	63.7	1.4	10.1	0.6	73.8	2.0	9.6	0.9	83.3	2.9
TOTAL (GW)	8.4		65.1		10.7		75.3		10.5		86.2	

	2011				2012				2013			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
Capacity (GW) of new or in-use	9.6	0.8	92.9	3.7	11.7	1.2	104.6	4.9	10.9	1.6	115.5	6.5
TOTAL (GW)	10.4		96.6		12.9		109.5		12.5		117.4	

	2014				2015				2016			
	New Ons.	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**	**New Ons.**	**New Offs.**	**Use On.**	**Use Of.**
Capacity (GW) of new or in-use	11.4	1.5	126.9	8.0	9.8	3.0	136.7	11.0	10.9	1.6	147.6	12.6
TOTAL (GW)	12.9		128.8		12.8		147.7		12.5		160.2	

8.4. Drive-train technologies composition

Table 13 Composition of the two drive-train technologies (gearbox and direct drive) assessed in this project. The material concentration is expressed in t/GW.

	Gearbox	Direct drive
Cast iron	18323	20100
Al	1423	678
Cu	1348	4778
Cr	483	525
Ni	431	329
Mn	782	790
Mo	101	109
Zn	5500	5500
B	0	1
Dy	2	7
Nd	16	45
Pr	0	12
Tb	0	2
Polymers	4600	4600
Glass/CC	7781	8100
Steel	64908	84085